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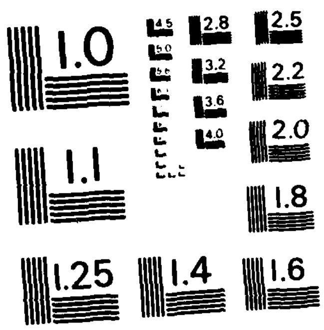

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Loran-C Nonprecision Approaches in the Northeast Corridor

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16. Abstract

This report describes a flight test designed to investigate the suitability of Loran-C as a nonprecision approach aid in the Northeast Corridor (NEC). Approaches were flown at six selected airports in the NEC by a CH-53A helicopter using Loran-C for course guidance. Accuracy criteria specified in Advisory Circular (AC) 90-45A were used as the standard for acceptability. Data were recorded for Loran in area calibrated and uncalibrated modes along with very high frequency omnidirectional radio range (VOR)/distance measuring equipment (DME) raw sensor data for comparison. The results show that the group repetition interval (GRI)-9960 Northeast U.S. Loran-C chain met AC 90-45A requirements for nonprecision approaches in all cases when a local area calibration was applied. The uncalibrated mode met AC 90-45A requirements at four of the six airports. It was determined that the Seneca, Nantucket, Carolina Beach triad should be used for navigation throughout the flight test area.

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Unclassified	Unclassified	74	

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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
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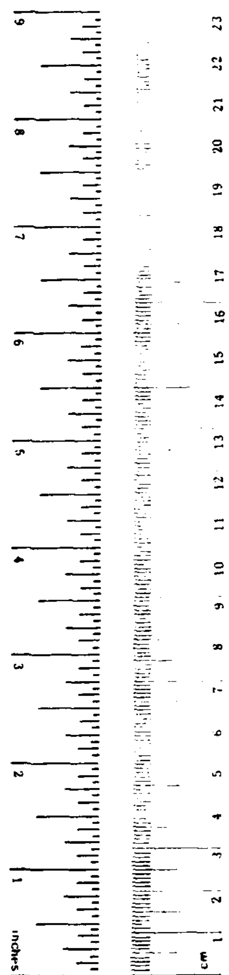
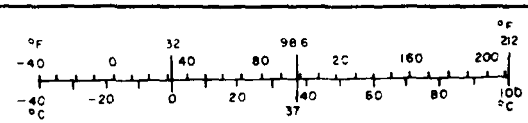
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 exactly [illegible]



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

The flight test evaluation described in this report is part of a Federal Aviation Administration (FAA) evaluation of Loran-C for aircraft navigational guidance. Advisory Circular (AC) 90-45A was used as a minimum specification for compliance. Other aspects of Loran performance not addressed in AC 90-45A were examined, including propagation anomalies, signal availability, and the local area calibration feature available in some receivers to increase accuracy performance.

Helicopter operators are the largest users of Loran-C because it is so well suited to typical helicopter operations. Loran is usable in remote locations not within conventional very high frequency omnidirectional radio range (VOR)/distance measuring equipment (DME) navigational coverage. Helicopter use is predicted to increase at least through the next decade, with the resultant increase in the need for instrument flight rule (IFR) operations. Size, weight, accuracy, signal availability, and the precision for user-definable waypoints make Loran very attractive to these users. Because of its chacteristics, Loran is useful both as an en route guidance system and as an instrument approach aid, and the FAA has decided to investigate its use for nonprecision approaches.

The Loran receiver selected for this flight test was the Teledyne TDL-711, the most popular airborne receiver in use. A pair of these receivers was instrumented, along with other aircraft systems, aboard a CH-53 helicopter. One each was operated in local area calibrated mode and uncalibrated mode. Availability of various Loran signals and accuracies involved in their use were investigated. VOR/DME data were collected for comparison purposes.

Six airports in the Northeast Corridor were selected and flights conducted in simulated IFR conditions. A portable tracking system was developed at the FAA Technical Center for use during the test. The tracker uses a dynamic ranging system and a Kalman filter computer routine to resolve position to better than 62 meters.

The report presents statistical and graphical data which show the following results:

1. Signals from only three transmitters are available at all subject airports; other signals available at two airports do not provide the required accuracy.

2. Accuracy of the uncalibrated receiver met AC 90-45A requirements at only two of the subject airports, but the local area calibration produced the desired accuracy at all airports. Also, a calibration made in Atlantic City produced the desired accuracy when flown at all four airports where data were available. In all cases, the local calibration improved or did not affect accuracy.

It was concluded that Loran-C is usable in the region for nonprecision approaches from the standpoint of navigational accuracy.

INTRODUCTION

The flight test evaluation described in this report is part of an ongoing Federal Aviation Administration (FAA) evaluation of Loran-C for all phases of helicopter navigation. Previous studies have addressed en route accuracies of Loran-C over various geographical areas, and results have generally been satisfactory. The next step in the evaluation process involves its use for nonprecision area navigation (RNAV) approaches.

OBJECTIVES.

Specific goals of this project are:

1. To collect data on Loran-C system errors to support decisions relative to the possible certification of Loran-C for nonprecision approaches in the Northeast Corridor (NEC). Accuracy criteria of Advisory Circular (AC) 90-45A are used to judge minimum levels of compliance for certification.

2. To obtain data on the flight technical error associated with Loran-C nonprecision approaches.

3. To obtain data on area propagation anomalies of Loran signals at various points in the NEC.

4. To obtain performance and operational data on Loran-C signals at various points in the NEC.

5. To examine the portability of the area calibration feature of certain Loran-C receivers over a large geographical area.

BACKGROUND.

Recent technological advancements have produced a rapid growth of the helicopter industry that is anticipated to continue into the next decade. A variety of factors have contributed to this growth, including advances in helicopter materials technology, expanded oil drilling and coal mining effort requiring support in remote areas, and the need for rapid transport from major airports to the downtown metropolitan areas they serve. As helicopters become more essential to transportation and commerce, all-weather capability becomes a necessity.

In recognition of this, the FAA is conducting an evaluation of helicopter navigation systems that will be used now and into the next century. Consideration of costs, accuracy, availability, dependability, and compatability with the National Airspace System (NAS) will enter into evaluation of all navigation systems that may meet user needs. Loran-C meets many of the requirements of helicopter operators because of its cost, weight, accuracy, availability, and its ability to provide RNAV to user defined waypoints.

LORAN-C OPERATION.

Loran-C is a hyperbolic radionavigation system created for maritime use, and is finding increased popularity among helicopter operators in remote areas. This system is based on low-frequency (100 kilohertz) transmission of timed, coded pulses with strictly controlled parameters. Transmitting stations at specific locations provide coverage of selected areas of the Northern Hemisphere.

Regional coverage is provided by groups of three to six transmitting stations called chains. Chains are distinguished by their group repetition interval (GRI), which corresponds to the period of the transmission sequence of all stations in the chain.

Each chain consists of a designated master station and several secondary stations. A transmission period begins when the master station sends a set of pulses, coded to identify it as a master. Each secondary then transmits its signal (figure 1) in turn, after a precisely controlled time delay.

Receiver position is derived by measuring time differences. Once the master signal is received, a clock is started and runs until the secondary signal is received. This measured time difference corresponds to the distance of the receiver from the transmitter and lies along a line of position (LOP) of constant time differences. Measured time differences from a second transmitter provide a second LOP; the intersection of these lines is the Loran-C position.

Coverage of the Northeast Corridor is provided by the Northeast U.S. Chain, GRI 9960 (figure 2). This chain consists of a master station in Seneca, New York, with secondaries in Caribou, Maine; Nantucket, Massachussetts; Carolina Beach, North Carolina; and Dana, Indiana.

AREA CALIBRATION. Area calibration is a feature of some Loran-C receivers (including the TDL-711 used in this test) which allows for correction of local bias in received Loran signals so that receiver calculated position coincides with surveyed position. The correction may be necessary due to propagation characteristics of Loran-C signals which vary over different types of terrain. The effect of these variations is to change the receiver-measured time difference (TD), which in turn causes a shift in calculated position. Because the TD to latitude/longitude (lat/long) model used in the receiver is optimized to certain propagation characteristics, variation of these characteristics causes a difference between surveyed lat/long and receiver calculated lat/long.

Correction is accomplished by entering a lat/long and corresponding TD's into the receiver. TD's may be measured by the receiver at the time of calibration and entered with the known lat/long at that point, or previously measured sets of lat/long and TD's which correspond to one geographical point may be input. With either method, the receiver computes the difference between expected TD's (based on the known lat/long entered) and the calibration (input) TD's. This bias is then used as a correction factor which is added to all succeeding TD measurements before lat/long computation. The position solution is, therefore, optimized to local propagation characteristics, but possibly degraded in other geographical areas. Area calibrated mode is not annunciated to the operator by the TDL-711.

RNAV NONPRECISION APPROACH ACCURACY REQUIREMENTS. Criteria for navigation accuracies are set forth in AC 90-45A, which describes navigation system errors in terms of total system crosstrack (TSCT), navigation crosstrack (NCT), flight technical error (FTE), and along-track error (ATE). Each is defined below, and their relationship is depicted in figure 3.

1. TSCT: This error is defined as the actual aircraft deviation perpendicular to the desired course in the horizontal reference plane.

2. NCT: This error is defined as the composite error perpendicular to the desired course in the horizontal reference plane, contributed by all navigation equipment including sensors, receivers, computers, displays, calibration scaling, or interconnecting errors peculiar to the system being evaluated.

3. FTE: This error is defined as the indicated aircraft deviation perpendicular to the desired course in the horizontal reference plane.

4. ATE: This error is defined as the actual aircraft deviation from the indicated position along the flightpath. ATE results from the total error contributions of the airborne and ground equipment only. No FTE is used in determining ATE.

As shown in figure 3, three system error terms combine in the direction perpendicular to the desired track. Statistically, NCT and FTE are combined in a root sum of squares (rss) manner to produce TSCT. The mathematical expression is:

$$TSCT = \sqrt{NCT^2 + FTE^2}$$

Algebraic manipulation yields an expression by which NCT may be derived when FTE and TSCT are specified:

$$NCT = \sqrt{TSCT^2 - FTE^2}$$

For the approach phase of flight, AC 90-45A specifies that TSCT must be less than 0.6 nautical mile (nmi), and FTE is budgeted at 0.5 nmi. The maximum allowable NCT, at the 95 percent confidence level computed in the rss manner described above, is 0.33 nmi; ATE is required to be less than 0.3 nmi.

DATA COLLECTION

Collection of data was organized into three phases. Development of a portable precision tracking system with accuracy in the ratio of 10:1 to the allowable error range of 0.0 to 0.3 nmi was required, along with a geographical survey of each site to obtain a position reference of sufficient quality to support the tracking system. Finally, RNAV approaches were flown in an instrumented CH-53 helicopter to collect navigation system accuracy data. The helicopter carried two instrumented TDL-711 Loran-C receivers manufactured by Teledyne Systems, Inc. and dual NCS-31 RNAV units manufactured by Collins Avionics. Each NCS-31 had inputs provided by a Collins VIR-30A very high frequency omnidirectional radio range (VOR) receiver and a Collins distance measuring equipment (DME)-40 receiver.

A total of six airports were selected for the flight test: Salisbury-Wicomico Airport, Salisbury, Maryland; Greater Wilmington Airport, Wilmington, Delaware;

Mercer County Airport, Trenton, New Jersey; Queen City Municipal Airport, Allentown, Pennsylvania; Rentschler Field, Hartford, Connecticut; and the FAA Technical Center, Atlantic City Airport, New Jersey. Approaches were flown at each airport while navigation system and aircraft parameters were recorded in digital format by an on-board computer.

PORTABLE TRACKING SYSTEM.

The positioning standard used to measure navigation system performance was a combination of hardware and software functions. A Motorola Mini Ranger IV provided raw distance measurements to each of four beacons located on the designated airfields. These data became an input to a Kalman filter post-processing routine that produced a lat/long position. Tracking system accuracy was previously determined by comparison of post-processed position with the Technical Center's precision tracking Nike-Hercules instrumentation radar. The 95 percent confidence level measured during accuracy tests at the Atlantic City Airport (ACY) was 61.4 meters.

The four beacons were placed at surveyed points on the airfield so as to maximize distance between them while maintaining a line-of-sight signal path to the helicopter at all points along the approach path.

A Kalman filter computer program developed at the Technical Center provided a linear mean square estimate of position and velocity vectors. It employed a dynamic system model of helicopter motion, a measurement model which related recorded data to states of the dynamic system model, a method of determining initial state vectors, and statistical knowledge of random processes associated with each model. A discussion of the model used for the Kalman filter is presented in appendix A. Accuracy of the tracking system is addressed in appendix B.

SITE SURVEY.

A survey was conducted at each test site to develop a set of reference coordinates required for the Mini Ranger portable tracking system. Distances from each of the beacon positions to the reference position (at known lat/long) were required for Kalman filter processing.

Absolute position fixes in WGS-72 coordinates were obtained with the JMR-4 Sea-Land Surveyor, manufactured by JMR Instruments. Manufacturer specified accuracy of the instrument is 5 meters. Relative distance measurements between beacon locations were made with a Hewlett-Packard laser rangefinder (HP 3810 Total Station), which measures distances accurately to within 1 inch. Trigonometric techniques were employed to determine relative distances between beacons in north-east-up (NEU) coordinates and one reference point in WGS-72 coordinates. This references point was then used as an origin for the tracking system which determined helicopter position in NEU coordinates. Lat/long (in WGS-72) was then derived from the reference position and the aircraft NEU position.

TEST FLIGHTS.

Flight tests were conducted at each of the subject airports under Instrument Flight Rules (IFR). The paths flown were approved public or private use RNAV approaches. In most cases the flights took place in visual meteorological conditions (VMC).

However, a screen was placed in front of the pilot's windshield to simulate instrument meteorological conditions (IMC). The safety pilot and crew kept watch for VFR traffic.

The flight crew consisted of four members: two pilots and two project personnel. The pilot flew the helicopter according to the steering information provided on his horizontal situation indicator (HSI). The copilot's job was to monitor aircraft performance, watch for traffic, and communciate with air traffic control (ATC) personnel. Project team members operated and monitored the Loran units, Mini Ranger, and data collection equipment. Duties were divided into those related to safe operation of the aircraft, the responsibility of the pilots, and directing the flight to achieve project goals, which was accomplished by the project crew.

A minimum of 15 approaches were flown at each airport, using steering information provided by each of three navigation configurations: the NCS-31 RNAV, Loran-C with an area calibration accomplished at that airport, and Loran-C with a calibration accomplished at the Technical Center. At least five approaches were flown in each configuration. The primary triad, in most cases, was made up of Seneca, Nantucket, and Carolina Beach. However, when other triads were available they were monitored during the NCS-31 RNAV approaches. When Loran steering was in use it was provided by a calibrated receiver (either local or ACY calibration), and the second TDL-711 was operated in the uncalibrated mode. Performance of both Loran units was comparable when they were configured similarly. Accuracy differences are, therefore, attributed to triad and calibration mode selection. Only one calibration was used for each configuration, i.e., receivers were not recalibrated for each flight, but used the same calibration parameters.

DATA ANALYSIS

Data analysis consisted of statistical and graphical characterization of error terms associated with each navigation system. Statistical data reduction was accomplished on a per second basis by summing the various error terms for each data sample over an entire approach, and expressing each as a mean and standard deviation. Using the tracking system as a reference, the following Loran error terms were computed for each data sample: TSCT, navigation northing (lat) error, navigation easting (long) error, NCT, and ATE. Raw sensor errors for VOR/DME were computed in the north, east, crosstrack, and along-track directions. Data were also plotted on a CALCOMP 4051 plotter to provide a clearer view of the patterns and trends of the error terms.

The first step in post-processing the data was to calculate actual aircraft position at each data point using the Kalman filter and the raw ranges measured in the aircraft during flight. Filter output was in NEU coordinates, converted to lat/long by referencing the NEU coordinate system to a known lat/long in WGS-72 coordinates. All calculations (except FTE) were then carried out in WGS-72 lat/long. TSCT was determined by computing the desired course from waypoint coordinates and calculating aircraft deviation perpendicular to this course. Navigation crosstrack and along-track terms were computed by taking differences in lat/long between each Loran computed position and the actual position. These differences were rotated into the direction of the desired course to determine NCT and ATE for each approach. VOR/DME sensor errors were computed similarly, after

first converting distance and angle measurement from known very high frequency omnidirectional radio range tactical air navigation aid (VORTAC) position to lat/long.

Once the error terms were expressed as a mean and standard deviation, two-dimensional (2D) mean and 2 distance root mean squared (drms) values were calculated. The 2D mean is the vector sum of NCT and ATE; the 2 drms is the radius of a circle containing 95 percent of all possible fixes that can be obtained with a system at any one place. The mathematical expressions used were:

$$\text{2D mean} = \sqrt{(\text{mean NCT})^2 + (\text{mean ATE})^2}$$

$$\text{2 drms} = 2 \times \sqrt{(\text{NCT standard deviation})^2 + (\text{ATE standard deviation})^2}$$

Then, total navigation system errors were calculated using:

$$\text{Navigation system error} = \text{2D mean} + \text{2 drms}$$

to provide a 95 percent confidence interval. Ninety-five percent limits were also calculated for TSCT and FTE using:

$$\text{TSCT} = \text{Mean TSCT} + 2\sigma, \text{ and}$$

$$\text{FTE} = \text{Mean FTE} + 2\sigma, \text{ respectively.}$$

Since the pilots' HSI needle deflection indicates deviation from the desired course and is directly influenced by pilot actions, it provides a direct measure of FTE. The needle deflection was recorded in microamps and converted to nmi, based on Loran constant course width of ±1.26 nmi.

RESULTS

Accuracy results from each airport are presented in tables 1 through 28. Results show mean and 2σ crosstrack, along-track, northing (lat), and easting (long) errors, with the number of samples for each data run (approach) under each flight test condition. Results are summarized in table 29, which presents 2D navigation system errors for each airport under each test condition. A Loran TSCT summary appears in table 30, which presents the mean plus 2σ TSCT at each airport under each test condition. Note that only calibrated receiver TSCT is available as it was the only receiver configured to present guidance information to the pilot.

The sign convention adopted is that a positive NCT error is to the right of the desired course. FTE, presented as a single number (mean plus 2σ) in table 31 for each airport in the flight test, is positive for a fly right command, indicating that the pilot is left of course.

The abbreviations MXY and MYZ appearing in the tables and text indicate Loran triads in the GRI 9960 chain. M designates the master station, Seneca. The secondaries X, Y, and Z correspond to the stations in Nantucket, Carolina Beach, and Dana, respectively. The designations indicate that these triads were in use for navigation, and only Loran solutions computed using a particular triad appear in the data associated with it.

Representative plots of error terms, descent profiles, and approach plates for each airport are presented in figures 4 through 15. SNR plots are presented in figures 23 through 28 for each available Loran signal at each airport.

The high degree of consistency from one run to another in the navigation system errors and SNR's eliminate the need for detailed graphical analysis of each. Plots are presented to more effectively show the relationships of the various error terms to each other.

SALISBURY-WICOMICO COUNTY AIRPORT, SALISBURY, MARYLAND.

Statistics for the Salisbury approaches are presented in tables 1 through 5. They show 2D mean Loran errors using the MXY triad, and VOR/DME sensor errors all on the order of 0.2 nmi; 2D mean errors involved in use of the MYZ triad are on the order of 0.5 nmi. Very little variation is shown on different runs or with different Loran calibrations.

The effect of area calibration is seen in tables 1 through 3. The 2D mean error exhibits small variations, but the components change with the calibration. The uncalibrated receiver has a greater component in the crosstrack direction (about 0.2 nmi) than in the along-track direction (0.14 nmi). The ACY calibration improves the crosstrack magnitude, but changes the sign of the error. It has little effect on along-track error, resulting in an overall improvement in the 2D mean. The local calibration increases the crosstrack slightly, but virtually eliminates the along-track error; 2D mean is about the same with either calibration applied.

Use of the MYZ triad caused 2D mean errors on the order of 0.5 nmi, as shown in table 4. The components are approximately 0.4 nmi mean crosstrack and 0.3 nmi mean in the along-track direction.

VOR/DME 2D mean sensor errors (table 5) are virtually the same as the uncalibrated Loran. Sensor error in the crosstrack direction is similar to NCT with the opposite sign, while error in the direction of the track is slightly better. Characteristically, the 2 drms values for VOR/DME are an order of magnitude greater than those for Loran.

Representative plots of a Salisbury approach appear in figure 4. The crosstrack plot shows a changing bias for all three receivers, which is actually an angular error characteristic of the tracking system. The causes and effects of these characteristics on position determination accuracy are described in appendix C. The Salisbury approach plate is presented in figure 5.

GREATER WILMINGTON AIRPORT, WILMINGTON, DELAWARE.

Statistical data for the Wilmington approaches are presented in tables 6 through 10. The uncalibrated Loran shows 2D mean errors of about 0.25 nmi,

predominantly in the along-track direction. Application of the local calibration (table 6) causes sign reversals and magnitude reductions in both crosstrack and along-track error terms, resulting in total mean error of under 0.1 nmi. The ACY calibration (table 7) shows slightly increased magnitudes in both directions, with resultant 2D mean still under 0.15 nmi. The MYZ triad data (table 9) show along-track errors increased in magnitude by about 0.3 nmi over the MXY triad data, and a large 2 drms in table 9, run 5, due to low Dana SNR. Otherwise, MXY and MYZ 2 drms values are comparable.

VOR/DME mean sensor errors presented in table 10 were under 0.1 nmi, with the predominant component in the crosstrack direction. As with Salisbury data, 2 drms values are much greater for VOR/DME than for Loran.

The Wilmington approach used is presented in figure 6, and plots of a representative approach are presented in figure 7.

MERCER COUNTY AIRPORT, TRENTON, NEW JERSEY.

Statistics characterizing errors measured during the Trenton approaches are presented in tables 11 through 14. The uncalibrated receiver (table 13) exhibits errors on the order of 0.35 nmi for 2D mean, composed of 0.3 nmi crosstrack and along-track under 0.1 nmi. Entering the ACY calibration (table 12) reduces the crosstrack error to about 0.05 nmi and changes ATE by about 0.15 nmi for a 2D mean position error of approximately 0.09 nmi. The local calibration further reduces errors to well under 0.1 nmi with symmetrical CTE and ATE, as shown in table 11.

Table 14 shows VOR/DME 2D mean sensor errors under 0.1 nmi, with a slightly greater component in the crosstrack than the along-track direction. Two drms values are greater than those at Salisbury and Wilmington because at these two airports the RNAV approaches utilized on field VORTAC's, but the Mercer County approach used a VORTAC 5 miles from the field.

The Trenton approach plate is presented in figure 8, representative plots are shown in figure 9.

QUEEN CITY MUNICIPAL AIRPORT, ALLENTOWN, PENNSYLVANIA.

Allentown statistics are presented in tables 15 through 18. Uncalibrated Loran 2D means (table 17) were approximately 0.17 nmi, almost entirely in the along-track direction. The ACY calibration (table 16) degraded the position accuracy to about 0.26 nmi (2D mean). The local calibration (table 15) improved mean accuracy to 0.07 nmi, almost totally in the along-track direction.

Allentown was the only test site at which the ACY calibration made the solution noticeably worse than the uncalibrated solution. It is also the only site at which all three Loran signals traveled primarily overland to reach the site. Loran signal propagation characteristics may cause variations in position determination, based on varying surface conductivity along the propagation path. The reasons for this are explained in the section on "Comparison of Results."

VOR/DME results (table 18) show 2D means generally under 0.15 nmi, with one entry of 0.2 nmi. The crosstrack component shows much greater variation than the along-track. Results were slightly better than the uncalibrated Loran — but not

as good or as repeatable as the Loran with local calibration. Two drms values were large because the VORTAC used for the approach is 7 miles from the field. The 2 drms entry for run 4 is extremely large and its source (ground or airborne) cannot be identified. However, the 2D mean is not excessively large.

The approach plate for Allentown is shown in figure 10, representative plots of Allentown data appear in figure 11. A plot of VOR/DME sensor errors could not be obtained due to in-flight failure of the pilot's navigation switching system.

RENTSCHLER FIELD, EAST HARTFORD, CONNECTICUT.

Hartford results are presented in tables 19 through 21. The local calibration (table 19) produced 2D mean errors under 0.1 nmi, equally in the crosstrack and along-track directions. The uncalibrated receiver (table 20) produced crosstrack errors of almost 0.2 nmi, small along-track errors, and a 2D mean on the order of 0.2 nmi. VOR/DME errors in table 21 show crosstrack near 0.3 nmi and along-track of about 0.15 nmi, for a 2D mean of up to 0.33 nmi. Data on the ACY calibration was unavailable because a change made in Mini Ranger beacon geometry to improve signal reception caused excessive geometrical dilution of precision of the tracking system.

Figure 12 shows the approach, figure 13 shows representative plots of the Hartford data.

FAA TECHNICAL CENTER, ATLANTIC CITY AIRPORT, NEW JERSEY.

Statistics on Technical Center approaches are presented in tables 22 through 28. The uncalibrated receiver (table 23) exhibited an overall error of approximately 0.35 nmi, comprised of a 0.3 nmi crosstrack component and a 0.14 nmi along-track component. The local area calibration reduced 2D mean error to 0.04 nmi (as shown in table 22).

VOR/DME exhibited errors on the order of 0.04 nmi, with symmetrical components (table 24).

The ACY approach is shown in figure 14, and representative plots in figure 30.

COMPARISON OF RESULTS.

Results of the flight test comparing accuracies at each airport with the others are presented in tables 29 and 30. The total 2D navigation system errors are presented in table 29. This value is shown at each airport for Loran with the local calibration applied, with the ACY calibration applied, in the uncalibrated mode, and VOR/DME sensor error for comparison purposes. Also presented are 2D navigation system errors at each airport, with the calibration from the subject airport flown at ACY, and the distance between the subject airport and ACY. Table 30 shows Loran TSCT at each airport with local and ACY calibrations, and the subject calibration flown at ACY. These 95 percent confidence levels provide the comparison for AC 90-45A compliance. A value of 0.5 nmi was used for FTE, as set forth in AC 90-45A, and combined in an rss manner to produce the values of TSCT presented.

Table 29 shows that the calibrated receiver at all test sites met AC 90-45A approach accuracy requirements for all directions of flight, regardless of whether

the calibration was local or from ACY. The uncalibrated receiver met these requirements at Allentown and Wilmington only. VOR/DME results, presented for comparison, ranged from 0.27 nmi (Wilmington) to 0.84 nmi (Allentown). It must be stressed, however, that these are raw sensor errors, without the filtering and smoothing carried out in the RNAV computer. These errors would be encountered when making a VOR or VOR/DME approach. But the RNAV approach, using a computer and filtering techniques, allows better accuracy due to its inherently more precise method of position determination.

As shown in table 29, Loran-C in the uncalibrated mode exhibited fairly uniform accuracies throughout the flight test area, but with some minor variations. The most likely explanation lies in the characteristics of the medium along the propagation path.

Surface conductivities underlying the propagation path affect transmission of electromagnetic radiation. This effect is accounted for in the Loran receiver by modeling the earth conductivity in the region between the transmitter and receiver, and adjusting the position (lat/long) grid accordingly. The factor which affects propagation the most is the ratio of the transmission path overland to that overwater, due to the great difference in conductivity.

Figure 16 shows the test airports and the Loran transmitters primarily used in the flight test. The length of the propagation path and the percentage of it which is overwater are entered in table 29. These data show that the Seneca and Carolina Beach signals travel primarily overland to reach each of the test airports. The Nantucket signal travels primarily overwater, but nearly two-thirds of its path to Allentown lies overland.

It is this propagation effect which most likely explains the results in Allentown where the uncalibrated receiver performed best. Results at other airports vary, generally, with percentages of overwater portions of propagation paths.

Figures 17 through 22 show variation of crosstrack and along-track mean errors with heading at each subject airport with each of the three Loran configurations: uncalibrated, with an ACY calibration, and with a local calibration. These figures show directly the effects of area calibration in reducing the magnitude of the error and changing its phase. They are also useful in estimating crosstrack and along-track errors which would be encountered in various directions of flight.

Loran TSCT, presented in table 30, is equal to or better than 0.60 nmi within a 95 percent confidence interval with either calibration applied at all airports. All entries, therefore, met AC 90-45A accuracy requirements for nonprecision approaches. FTE (table 31) was always less than 0.20 nmi, also meeting AC 90-45A requirements at the 95 percent confidence level. These numbers should not be compared directly with 2D system error terms because TSCT does not include, by definition, any along-track error.

AREA CALIBRATION COMPARATIVE RESULTS.

The portability of an area calibration may be determined by examining differences between accuracies measured using a local calibration and one from another location. Results from individual airports show that the ACY calibration usually improved or did not substantially affect accuracy when compared to the uncalibrated

receiver. Only Allentown showed noticeably degraded accuracy when the calibration was applied.

Area calibration from subject airports, when flown at the Technical Center, improved accuracies over the uncalibrated mode in three of four cases, and the other decreased only 0.04 nmi. Results in table 29 show accuracies involved in the use of the Salisbury, Trenton, Allentown, and Hartford calibrations.

The Salisbury calibration produced the best results when flown at ACY. However, the ACY calibration did not produce such good results in Salisbury. Since both calibrations appear to work equally well at both airports, the area calibration apparently does not correct for propagation disturbance in the Salisbury area. This is probably due to low SNR from the Nantucket signal (shown in figure 23).

Table 29 also shows that the area calibration gets noticeably worse as distance north of ACY is increased. Salisbury, which is south of ACY, and Trenton calibrations produced errors under 0.17 nmi when flown at ACY. But Allentown and Hartford calibrations produced 0.34 and 0.43 nmi errors, respectively. The ACY calibration flown at these sites generally gets progressively worse moving away from ACY, and appears to depend directly on distance from the calibration site.

At all subject airports, the local area calibration was at least as effective as the ACY calibration flown at that airport. At Trenton, Wilmington, and Salisbury, the results were nearly the same for either calibration. At Allentown the improvement is much more pronounced, due to propagation characteristics previously described.

Data on area calibration of the Seneca, Carolina Beach, Dana triad were not available. It was expected that a calibration would substantially reduce errors derived for use of this triad. However, the extent of the improvement cannot be conclusively determined without further testing.

LORAN-C SIGNAL-TO-NOISE RATIO RESULTS.

Plots of individual signal-to-noise ratio (SNR) in decibels (dB) are presented in figures 23 through 28. These plots show a correlation between received signal strength and distance from the transmitter, which should be expected. The Salisbury plots (figure 23) show relatively stronger signals from Seneca and Carolina Beach. The Nantucket signal varies between -5 and -10 dB and is at the lower limit of the receiver's sensitivity. It can, therefore, affect position determination accuracy, which depends on an accurate tracking of the third oscillation of the Loran signal waveform. The Dana signal shows lower and more variant SNR, frequently dropping below -10 dB.

In Wilmington (figure 24) signal strengths improve because the stations, except for Carolina Beach, are closer. Dana is still available at Wilmington but not at the airports further north and east.

ACY SNR's (figure 25) show improving Seneca and Nantucket signals. Moving toward the north produces decreasing Carolina Beach signal and increases Seneca and Nantucket SNR's. The trend is apparent in plots from Trenton, Allentown, and Hartford (figures 26, 27, and 28, respectively).

The TDL-711 receiver used in this flight test will operate using signals in the range of -5 to -10 dB. Operation in this range may, however, cause degradation of position accuracy. The maximum SNR that can be computed by the receiver before signal limiting is 5 dB. The Caribou signal was not received at any of the subject airports.

SUMMARY OF RESULTS.

1. Loran-C in area calibrated mode met AC 90-45A nonprecision approach requirements for navigation crosstrack, along-track, and TSCT at all subject airports. Application of either the local area calibration or the ACY calibration (where data were available) produced adequate accuracy for compliance.

2. Loran-C in uncalibrated mode met the requirements of AC 90-45A at two of the six test sites: Greater Wilmington and Queen City Municipal (Allentown).

3. FTE involved in use of Loran-C for nonprecision approaches was always less than 0.2 nmi at the 95 percent confidence level, meeting the limit established by AC 90-45A.

4. Loran-C signal strengths were adequate for navigation at all test airports using the Seneca, Nantucket, Carolina Beach triad. The Seneca, Carolina Beach, Dana triad is available at Salisbury and Wilmington. Signal strength was dependent upon signal propagation distance, and no anomalies were observed.

5. Local area calibration improved accuracies over the uncalibrated mode at all the subject airports.

6. The ACY calibration improved accuracy over the uncalibrated receiver at all airports except Allentown. This was attributed to terrain differences affecting propagation of Loran signals at the different airports.

7. Area calibrations from the test sites flown at Atlantic City produced results dependent upon distance from the calibration area. Calibrations made fairly close to ACY produced good results, while calibrations made further away showed decreased accuracy, becoming worse than the uncalibrated receiver and exceeding AC 90-45A limits.

8. Loran TSCT in all cases was at or below the required 0.6 nmi, and both FTE and navigation crosstrack were at or below the limits established by AC 90-45A.

CONCLUSIONS

1. Loran-C in the area calibrated mode met Advisory Circular (AC) 90-45A nonprecision approach navigation crosstrack, along-track, flight technical error (FTE), and total system crosstrack (TSCT) at all subject airports in the Northeast Corridor, when using the Seneca, Nantucket, Carolina Beach triad of the group repetion interval (GRI) 9960 chain.

2. FTE associated with use of Loran-C is below the 0.5 nautical mile (nmi) limit established by AC 90-45A.

3. No Loran-C signal propagation anomalies were observed at any of the subject airports.

4. The Seneca, Nantucket, Carolina Beach triad (MXY) was available at all airports tested. The Dana signal was available in the western portion of the flight test area. Use of the Seneca, Carolina Beach, Dana triad (MYZ) produced much greater errors than the MXY triad. It is anticipated that an area calibration would reduce these errors. The MXY triad should be used primarily throughout the flight-test area because the Dana signal, even when available, has marginal strength for accurate tracking.

5. The area calibration is effective within a regional area, the extent of which cannot be determined from the amount of testing done. Accuracy decreases as distance from the calibration point increases. Also, the calibration may not be effective in an area which may be nearby but has largely different propagation characteristics.

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TABLE 1. SALISBURY RESULTS — LORAN MXY TRIAD, LOCAL CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.14	0.06	-0.18	0.08	0.22	0.10	0.01	0.04	263	0.22	0.10
2	0.13	0.04	-0.17	0.06	0.22	0.06	0.00	0.04	263	0.22	0.07
3	0.14	0.04	-0.18	0.08	0.23	0.08	0.01	0.04	250	0.23	0.09
4	0.14	0.06	-0.19	0.08	0.24	0.08	0.01	0.04	258	0.24	0.09
5	0.13	0.06	-0.18	0.08	0.22	0.12	0.00	0.02	250	0.22	0.12

TABLE 2. SALISBURY RESULTS — LORAN MXY TRIAD, ACY CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0	0.06	-0.21	0.08	0.17	0.08	-0.12	0.04	280	0.21	0.09
2	-0.01	0.06	-0.18	0.08	0.14	0.08	-0.11	0.04	307	0.18	0.09
3	-0.01	0.10	-0.20	0.10	0.14	0.10	-0.13	0.10	253	0.20	0.14
4	0	0.04	-0.19	0.08	0.16	0.08	-0.11	0.04	211	0.19	0.09
5	0.01	0.06	-0.21	0.04	0.18	0.08	-0.11	0.02	226	0.21	0.08

TABLE 3. SALISBURY RESULTS — LORAN MXY TRIAD, UNCALIBRATED

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	-0.02	0.06	0.23	0.08	-0.20	0.10	0.12	0.04	274	0.23	0.11
2	-0.02	0.06	0.27	0.08	-0.23	0.08	0.14	0.06	312	0.27	0.10
3	-0.03	0.28	0.26	0.28	-0.22	0.12	0.13	0.36	205	0.26	0.38
4	-0.01	0.04	0.25	0.08	-0.21	0.08	0.13	0.04	214	0.25	0.09
5	-0.01	0.06	0.23	0.06	-0.19	0.08	0.13	0.02	229	0.23	0.08
6	-0.01	0.06	0.24	0.10	-0.20	0.10	0.14	0.04	264	0.24	0.11
7	-0.01	0.04	0.25	0.06	-0.20	0.06	0.14	0.04	265	0.24	0.07
8	0	0.04	0.24	0.08	-0.19	0.06	0.15	0.06	253	0.24	0.08
9	0	0.06	0.23	0.08	-0.19	0.10	0.14	0.04	262	0.24	0.11
10	-0.01	0.08	0.24	0.10	-0.20	0.12	0.13	0.01	252	0.24	0.12

TABLE 4. SALISBURY RESULTS — LORAN MYZ TRIAD, UNCALIBRATED

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	-0.01	0.16	0.47	0.18	-0.38	0.22	0.27	0.04	279	0.47	0.22
2	-0.01	0.10	0.49	0.10	-0.40	0.14	0.29	0.06	256	0.49	0.15
3	0.01	0.18	0.51	0.14	-0.40	0.18	0.31	0.14	271	0.51	0.11
4	-0.01	0.12	0.52	0.14	-0.43	0.18	0.30	0.04	266	0.52	0.18
5	0.02	0.04	0.51	0.08	-0.40	0.08	0.32	0.06	278	0.51	0.10

TABLE 5. SALISBURY RESULTS — VOR/DME SENSOR ERRORS

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.19	0.22	-0.13	0.22	0.22	0.30	0.08	0.08	287	0.23	0.31
2	0.18	0.14	-0.12	0.16	0.20	0.20	0.10	0.08	257	0.22	0.22
3	0.20	0.20	-0.13	0.18	0.22	0.26	0.09	0.10	281	0.24	0.28
4	0.19	0.18	-0.12	0.16	0.21	0.22	0.08	0.10	267	0.22	0.24
5	0.22	0.10	-0.13	0.14	0.23	0.16	0.10	0.08	279	0.25	0.18
6	0.18	0.12	-0.16	0.14	0.23	0.18	0.05	0.06	283	0.24	0.19
7	0.17	0.10	-0.14	0.14	0.21	0.16	0.06	0.08	313	0.22	0.18
8	0.14	0.12	-0.14	0.14	0.19	0.16	0.03	0.10	254	0.19	0.19
9	0.17	0.08	-0.14	0.14	0.21	0.14	0.06	0.10	214	0.22	0.17
10	0.20	0.10	-0.16	0.10	0.25	0.12	0.07	0.08	230	0.26	0.14
11	0.19	0.14	-0.14	0.16	0.22	0.18	0.07	0.08	265	0.23	0.20
12	0.19	0.08	-0.14	0.12	0.23	0.12	0.07	0.08	266	0.24	0.14
13	0.20	0.08	-0.14	0.14	0.23	0.14	0.08	0.08	254	0.24	0.16
14	0.20	0.10	-0.13	0.14	0.23	0.14	0.08	0.10	263	0.24	0.17
15	0.19	0.12	-0.14	0.14	0.22	0.18	0.07	0.08	253	0.23	0.20

TABLE 6. WILMINGTON RESULTS — LORAN MXY TRIAD, LOCAL CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.01	0.08	-0.07	0.04	-0.03	0.08	0.07	0.04	281	0.08	0.09
2	0.00	0.04	-0.07	0.02	-0.02	0.04	0.07	0.02	238	0.07	0.04
3	0.01	0.08	-0.07	0.02	-0.02	0.08	0.07	0.04	180	0.07	0.09
4	0.00	0.04	-0.07	0.02	-0.02	0.04	0.06	0.02	257	0.06	0.04
5	-0.01	0.04	-0.07	0.02	-0.01	0.04	0.07	0.02	250	0.07	0.04

TABLE 7. WILMINGTON RESULTS — LORAN MXY TRIAD, ACY CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.06	0.06	-0.12	0.04	-0.08	0.06	0.10	0.02	221	0.13	0.06
2	0.06	0.08	-0.12	0.04	-0.08	0.08	0.10	0.02	310	0.13	0.08
3	0.04	0.04	-0.13	0.08	-0.10	0.04	0.11	0.08	313	0.15	0.09
4	0.05	0.04	-0.12	0.02	-0.07	0.04	0.11	0.02	314	0.13	0.04

TABLE 8. WILMINGTON RESULTS — LORAN MXY TRIAD, UNCALIBRATED

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.04	0.04	0.26	0.04	0.02	0.06	-0.26	0.02	224	0.26	0.06
2	0.04	0.08	0.26	0.04	0.02	0.08	-0.26	0.02	315	0.26	0.08
3	0.03	0.04	0.25	0.08	0	0.04	-0.26	0.08	320	0.26	0.09
4	0.03	0.04	0.26	0.02	0.03	0.04	-0.26	0.02	318	0.26	0.04
5	0.05	0.08	0.27	0.02	0.01	0.08	-0.27	0.02	281	0.27	0.08
6	0.04	0.04	0.27	0.02	0.02	0.04	-0.27	0.02	240	0.27	0.04
7	0.04	0.08	0.27	0.02	0.02	0.08	-0.27	0.04	185	0.27	0.09
8	0.04	0.02	0.27	0.02	0.02	0.02	-0.27	0.02	258	0.27	0.03
9	0.03	0.04	0.27	0.02	0.03	0.04	-0.27	0.02	253	0.27	0.04

TABLE 9. WILMINGTON RESULTS — LORAN MYZ TRIAD, UNCALIBRATED

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.01	0.04	0.54	0.04	0.11	0.06	-0.53	0.04	63	0.54	0.07
2	0.02	0.04	0.54	0.04	0.10	0.04	-0.53	0.04	66	0.54	0.06
3	0.02	0.04	0.52	0.06	0.09	0.04	-0.51	0.06	276	0.52	0.07
4	0.02	0.04	0.53	0.06	.09	0.04	-0.52	0.06	278	0.53	0.07
5	0.03	0.04	0.54	0.06	0.05	0.32	-0.50	0.26	330	0.50	0.41

TABLE 10. WILMINGTON RESULTS — VOR/DME SENSOR ERRORS

Run	North Mean	North 2σ	East Mean	East 2σ	NCT Mean	NCT 2σ	ATE Mean	ATE 2σ	Sample Size	2D Mean	2 drms
1	-0.02	0.16	0	0.08	0.02	0.18	0.01	0.08	226	0.02	0.20
2	-0.05	0.20	0.01	0.10	0.06	0.20	0.00	0.08	316	0.06	0.22
3	-0.07	0.16	0.00	0.10	0.04	0.18	0.01	0.10	321	0.04	0.21
4	-0.07	0.16	0.01	0.08	0.07	0.18	0.01	0.08	319	0.07	0.20
5	-0.09	0.20	0.01	0.08	0.09	0.20	0.01	0.08	279	0.09	0.22
6	-0.15	0.22	0.03	0.08	0.16	0.24	0.01	0.08	67	0.16	0.25
7	-0.06	0.20	0.01	0.10	0.07	0.20	0.00	0.08	277	0.07	0.22
8	-0.07	0.18	0.01	0.08	0.07	0.18	0.01	0.08	278	0.07	0.20
9	-0.05	0.18	0.00	0.08	0.05	0.18	0.01	0.06	330	0.05	0.19
10	-0.04	0.20	0.01	0.10	0.04	0.20	0.00	0.08	282	0.04	0.22
11	-0.03	0.12	0.00	0.08	0.03	0.12	0.00	0.08	241	0.03	0.14
12	-0.08	0.20	0.02	0.08	0.08	0.20	0.01	0.08	187	0.08	0.22
13	-0.08	0.16	0.02	0.08	0.08	0.16	0.00	0.08	258	0.08	0.18
14	-0.08	0.16	0.01	0.10	0.08	0.18	0.01	0.08	254	0.08	0.20

TABLE 11. TRENTON RESULTS — LORAN MXY TRIAD, LOCAL CALIBRATION

Run	North Mean	North 2σ	East Mean	East 2σ	NCT Mean	NCT 2σ	ATE Mean	ATE 2σ	Sample Size	2D Mean	2 drms
1	-0.01	0.04	0.03	0.04	-0.02	0.04	-0.03	0.04	166	0.04	0.06
2	-0.01	0.04	0.05	0.06	-0.03	0.06	-0.03	0.04	190	0.04	0.07
3	0.01	0.10	0.03	0.12	-0.03	0.16	-0.02	0.04	186	0.04	0.16
4	-0.02	0.04	0.07	0.08	-0.08	0.08	-0.04	0.02	191	0.09	0.08

TABLE 12. TRENTON RESULTS — LORAN MXY TRIAD, ACY CALIBRATION

Run	North Mean	North 2σ	East Mean	East 2σ	NCT Mean	NCT 2σ	ATE Mean	ATE 2σ	Sample Size	2D Mean	2 drms
1	0.08	0.04	0	0.08	-0.04	0.10	0.07	0.04	194	0.08	0.10
2	0.09	0.06	0.00	0.06	-0.05	0.10	0.08	0.04	156	0.09	0.09
3	0.09	0.04	0.01	0.04	-0.05	0.04	0.08	0.06	203	0.09	0.07
4	0.08	0.04	0.01	0.02	-0.05	0.02	0.08	0.04	184	0.09	0.04
5	0.07	0.04	0.02	0.02	-0.05	0.02	0.08	0.02	178	0.09	0.03

TABLE 13. TRENTON RESULTS — LORAN MXY TRIAD, UNCALIBRATED

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.11	0.06	0.33	0.08	-0.33	0.10	-0.08	0.02	195	0.34	0.10
2	0.13	0.04	0.32	0.06	-0.33	0.06	-0.08	0.02	159	0.34	0.06
3	0.13	0.04	0.32	0.04	-0.34	0.02	-0.09	0.04	210	0.35	0.04
4	0.13	0.04	0.32	0.02	-0.34	0.02	-0.07	0.02	187	0.35	0.03
5	0.12	0.04	0.32	0.02	-0.35	0.02	-0.08	0.02	179	0.36	0.03
6	0.13	0.04	0.30	0.02	-0.32	0.04	-0.07	0.02	67	0.33	0.04
7	0.12	0.04	0.32	0.06	-0.33	0.06	-0.08	0.04	193	0.34	0.07
8	0.14	0.12	0.30	0.10	-0.33	0.16	-0.07	0.04	186	0.34	0.16
9	0.12	0.04	0.33	0.08	-0.37	0.08	-0.08	0.04	194	0.38	0.09

TABLE 14. TRENTON RESULTS — VOR/DME SENSOR ERRORS

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.08	0.30	0.04	0.36	0.08	0.20	0.05	0.42	196	0.09	0.47
2	0.07	0.20	0.04	0.30	0.07	0.16	0.04	0.32	160	0.08	0.36
3	0.06	0.24	0.05	0.30	0.08	0.16	0.02	0.36	211	0.08	0.39
4	0.08	0.22	0.04	0.28	0.08	0.16	0.04	0.32	188	0.04	0.36
5	0.08	0.10	0.04	0.14	0.09	0.08	0.04	0.16	180	0.10	0.18
6	0.09	0.16	0.03	0.24	0.07	0.16	0.06	0.20	168	0.09	0.26
7	0.08	0.24	0.03	0.30	0.07	0.16	0.05	0.36	194	0.09	0.39
8	0.09	0.24	0.04	0.30	0.09	0.16	0.05	0.04	187	0.10	0.16
9	0.11	0.26	0.02	0.32	0.07	0.20	0.09	0.36	195	0.11	0.41

TABLE 15. ALLENTOWN RESULTS — LORAN MXY TRIAD, LOCAL CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	-0.03	0.02	-0.06	0.02	0	0.02	-0.07	0.02	192	0.07	0.03
2	-0.04	0.02	-0.06	0.02	0	0.02	-0.07	0.02	202	0.07	0.03
3	-0.03	0.02	-0.06	0.02	0	0.02	-0.07	0.02	220	0.07	0.03
4	-0.05	0.02	-0.05	0.02	-0.02	0.02	-0.07	0.02	173	0.07	0.03
5	-0.05	0.02	-0.05	0.02	-0.02	0.02	-0.07	0.02	177	0.07	0.03

TABLE 16. ALLENTWON RESULTS — LORAN MXY TRIAD, ACY CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.11	0.02	-0.23	0.02	-0.25	0.02	0.01	0.02	189	0.26	0.03
2	0.11	0.02	-0.23	0.02	-0.25	0.02	0.01	0.02	191	0.26	0.03
3	0.11	0.02	-0.23	0.02	-0.25	0.02	0.01	0.02	185	0.26	0.03
4	0.11	0.02	-0.23	0.02	-0.25	0.02	0.01	0.02	195	0.26	0.03
5	0.12	0.02	-0.23	0.02	-0.26	0.02	0.02	0.02	139	0.26	0.03

TABLE 17. ALLENTOWN RESULTS — LORAN MXY TRIAD, UNCALIBRATED

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.13	0.02	0.10	0.02	-0.02	0.02	0.16	0.02	193	0.16	0.03
2	0.13	0.02	0.11	0.02	-0.03	0.02	0.17	0.02	205	0.17	0.03
3	0.14	0.02	0.11	0.02	-0.03	0.02	0.18	0.02	220	0.18	0.03
4	0.15	0.02	0.10	0.02	-0.01	0.02	0.18	0.02	174	0.18	0.03
5	0.15	0.02	0.10	0.02	-0.01	0.02	0.18	0.02	178	0.18	0.03
6	0.13	0.02	0.10	0.02	-0.02	0.02	0.16	0.02	190	0.16	0.03
7	0.13	0.02	0.09	0.02	-0.01	0.02	0.16	0.02	192	0.16	0.03
8	0.13	0.02	0.09	0.02	-0.01	0.02	0.16	0.02	189	0.16	0.03
9	0.13	0.02	0.10	0.02	-0.02	0.02	0.16	0.02	198	0.16	0.03
10	0.13	0.02	0.10	0.02	-0.02	0.02	0.16	0.02	141	0.16	0.03

TABLE 18. ALLENTWON RESULTS — VOR/DME SENSOR ERRORS

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	-0.02	0.18	0.10	0.58	0.07	0.46	-0.07	0.40	171	0.10	0.61
2	-0.02	0.18	0.11	0.62	.07	0.46	-0.08	0.44	219	0.11	0.64
3	-0.03	0.20	0.12	0.52	-0.12	0.52	-0.04	0.20	191	0.13	0.56
4	-0.04	0.30	0.20	1.68	-0.20	1.70	-0.04	0.28	192	0.20	1.72
5	-0.05	0.20	0.13	0.54	-0.13	0.54	-0.05	0.20	190	0.14	0.58
6	-0.04	0.18	0.11	0.58	-0.11	0.58	-0.04	0.20	201	0.12	0.61
7	-0.06	0.24	0.12	0.64	-0.11	0.64	-0.06	0.24	142	0.13	0.68

TABLE 19. HARTFORD RESULTS — LORAN MXY TRIAD, LOCAL CALIBRATION

Run	North Mean	North 2σ	East Mean	East 2σ	NCT Mean	NCT 2σ	ATE Mean	ATE 2σ	Sample Size	2D Mean	2 drms
1	0.03	0.12	0.07	0.14	-0.05	0.12	0.06	0.14	83	0.08	0.18
2	0.04	0.10	0.04	0.16	-0.02	0.12	0.06	0.14	76	0.06	0.18
3	-0.02	0.02	-0.01	0.01	-0.01	0.01	-0.02	0.02	29	0.02	0.02
4	-0.06	0.02	0.01	0.02	-0.04	0.02	-0.05	0.02	39	0.06	0.03

TABLE 20. HARTFORD RESULTS — LORAN MXY TRIAD, UNCALIBRATED

Run	North Mean	North 2σ	East Mean	East 2σ	NCT Mean	NCT 2σ	ATE Mean	ATE 2σ	Sample Size	2D Mean	2 drms
1	0.15	0.10	-0.12	0.14	0.18	0.12	0.07	0.14	84	0.19	0.18
2	0.15	0.10	-0.15	0.16	0.20	0.12	0.06	0.16	79	0.21	0.20
3	0.09	0.02	-0.20	0.02	0.22	0.02	-0.02	0.02	30	0.22	0.03
4	0.05	0.02	-0.19	0.02	0.18	0.02	-0.05	0.02	40	0.19	0.03

TABLE 21. HARTFORD RESULTS — VOR/DME SENSOR ERROR

Run	North Mean	North 2σ	East Mean	East 2σ	NCT Mean	NCT 2σ	ATE Mean	ATE 2σ	Sample Size	2D Mean	2 drms
1	0	0.14	-0.31	0.32	0.27	0.26	-0.15	0.24	85	0.31	0.35
2	0.01	0.16	-0.33	0.32	0.29	0.24	-0.15	0.26	80	0.33	0.35
3	-0.01	0.14	-0.30	0.44	0.25	0.32	-0.15	0.32	31	0.29	0.45
4	-0.05	0.12	-0.33	0.40	0.26	0.30	-0.20	0.30	40	0.33	0.42

TABLE 22. TECHNICAL CENTER RESULTS — LORAN MXY TRIAD, LOCAL CALIBRATION

Run	North Mean	North 2σ	East Mean	East 2σ	NCT Mean	NCT 2σ	ATE Mean	ATE 2σ	Sample Size	2D Mean	2 drms
1	-0.02	0.04	-0.02	0.04	-0.01	0.04	0.03	0.06	296	0.03	0.07
2	-0.03	0.06	-0.02	0.02	-0.01	0.02	0.04	0.06	254	0.04	0.06
3	-0.02	0.04	-0.03	0.04	-0.02	0.02	0.03	0.04	269	0.04	0.04
4	-0.02	0.04	-0.03	0.04	-0.02	0.02	0.03	0.06	248	0.04	0.06
5	-0.02	[illegible]	-0.04	0.04	-0.02	0.02	0.03	0.06	258	0.04	0.06

TABLE 23. TECHNICAL CENTER RESULTS — MXY TRIAD, UNCALIBRATED

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	-0.02	0.08	0.35	0.04	0.32	0.02	-0.14	0.08	296	0.35	0.08
2	-0.03	0.06	0.35	0.02	0.32	0.04	-0.13	0.04	254	0.35	0.06
3	-0.02	0.04	0.34	0.02	0.31	0.02	-0.14	0.04	269	0.34	0.04
4	-0.02	0.04	0.34	0.04	0.31	0.02	-0.14	0.06	248	0.34	0.06
5	-0.02	0.06	0.34	0.04	0.31	0.02	-0.14	0.06	258	0.34	0.06

TABLE 24. TECHNICAL CENTER RESULTS — VOR/DME SENSOR ERROR

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.02	0.14	0.00	0.22	-0.01	0.24	-0.02	0.10	297	0.02	0.26
2	0.02	0.12	-0.01	0.12	-0.02	0.14	-0.01	0.08	255	0.02	0.16
3	0.01	0.10	0.02	0.12	0.01	0.14	-0.01	0.08	270	0.01	0.16
4	0.00	0.18	0.05	0.34	0.04	0.38	-0.02	0.08	249	0.04	0.39
5	0.00	0.20	0.03	0.38	0.03	0.42	-0.02	0.08	259	0.04	0.43

TABLE 25. TECHNICAL CENTER RESULTS — LORAN MXY TRIAD, SALISBURY CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2	Sample Size	2D Mean	2 drms
1	0.08	0.04	0.02	0.02	-0.02	0.02	-0.08	0.04	330	0.08	0.04
2	0.08	0.04	0.02	0.02	-0.02	0.02	-0.08	0.04	331	0.08	0.04
3	0.08	0.04	0.02	0.02	-0.02	0.02	-0.08	0.04	334	0.08	0.04
4	0.08	0.04	0.02	0.02	-0.02	0.02	-0.08	0.04	323	0.08	0.04
5	0.08	0.04	0.02	0.02	-0.02	0.02	-0.08	0.04	330	0.08	0.04

TABLE 26. TECHNICAL CENTER RESULTS — LORAN MXY TRIAD, TRENTON CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	-0.10	0.02	0.07	0.02	0.11	0.02	0.06	0.04	330	0.13	0.04
2	-0.10	0.04	0.08	0.02	0.11	0.02	0.06	0.04	331	0.13	0.04
3	-0.10	0.04	0.08	0.02	0.11	0.02	0.06	0.04	334	0.13	0.04
4	-0.10	0.04	0.08	0.02	0.11	0.02	0.06	0.04	323	0.13	0.04
5	-0.10	0.04	0.08	0.02	0.11	0.02	0.05	0.04	330	0.12	0.04

TABLE 27. TECHNICAL CENTER RESULTS — LORAN MXY TRIAD, ALLENTOWN CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	0.01	0.04	0.17	0.04	0.14	0.02	-0.08	0.06	216	0.16	0.06
2	0.01	0.04	0.18	0.02	0.15	0.02	-0.09	0.04	224	0.17	0.04
3	0.01	0.04	0.18	0.02	0.15	0.02	-0.09	0.04	200	0.17	0.04
4	0.02	0.04	0.18	0.02	0.15	0.02	-0.10	0.06	156	0.18	0.06

TABLE 28. TECHNICAL CENTER RESULTS — LORAN MXY TRIAD, HARTFORD CALIBRATION

	North		East		NCT		ATE				
Run	Mean	2σ	Mean	2σ	Mean	2σ	Mean	2σ	Sample Size	2D Mean	2 drms
1	-0.01	0.04	-0.39	0.02	-0.34	0.02	0.19	0.04	210	0.39	0.04
2	-0.01	0.04	-0.39	0.02	-0.35	0.02	0.19	0.04	210	0.40	0.04
3	-0.01	0.04	-0.39	0.02	-0.34	0.02	0.18	0.04	195	0.38	0.04
4	-0.01	0.04	-0.39	0.02	-0.35	0.02	0.18	0.04	197	0.39	0.04
5	-0.01	0.04	-0.39	0.02	-0.35	0.02	0.19	0.04	200	0.40	0.04

TABLE 29. SUMMARY OF NAVIGATION SYSTEM ERRORS AT TEST AIRPORTS

Airport	Loran Accuracy Local Calibration Flown At Subject Airport (nmi)	Loran Accuracy Subject Calibration Flown at ACY (nmi)	Loran ACY Calibration Flown at Subject Airport (nmi)	Loran Accuracy Uncalibrated (nmi)	VOR DME Sensor Error (nmi)	Distance from ACY (nmi)	Distance to Nantucket (nmi)	Portion Overwater (%)	Distance to Carolina Beach (nmi)	Portion Overwater (%)
Salisbury	0.33	0.13	0.33	0.41	0.51	79	306	92	288	19
Wilmington	0.16	-	0.21	0.31	0.27	48	280	71	360	5
Trenton	0.16	0.16	0.16	0.43	0.45	51	224	86	404	15
Allentown	0.10	0.34	0.27	0.22	0.84	78	284	30	410	8
Hartford	0.26	0.43	-	0.35	0.69	165	129	45	522	14
Atlantic City	0.10	-	-	0.39	0.31	0	234	43	366	14

TABLE 30. LORAN TSCT SUMMARY

Airport	Local Calibrated Subject Airport rss (nmi)	ACY Calibrated Subject Airport rss (nmi)	Subject Calibrated ACY rss (nmi)
Salisbury	0.60	0.60	0.52
Wilmington	0.52	0.54	--
Trenton	0.52	0.52	0.52
Allentown	0.51	0.57	0.60
Hartford	0.56	--	0.66
Atlantic City	0.51	--	--

TABLE 31. LORAN FTE AT SUBJECT AIRPORTS

Airport	Loran rss FTE (nmi) All Calibrations
Salisbury	-0.36
Wilmington	0.32
Trenton	0.23
Allentown	0.36
Hartford	-0.31
Atlantic city	-0.31

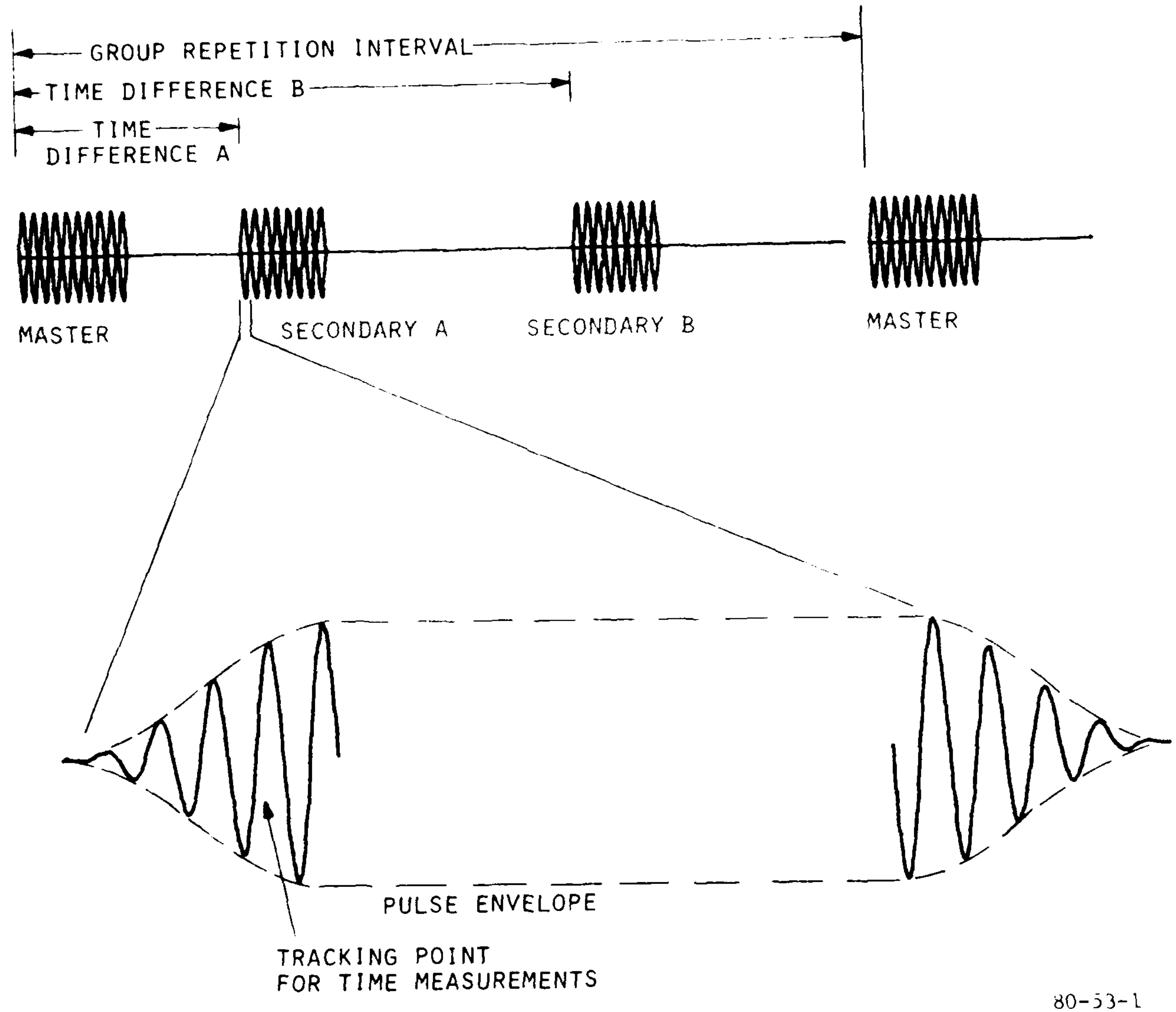

FIGURE 1. LORAN-C SIGNAL WAVEFORM

GRI 9960

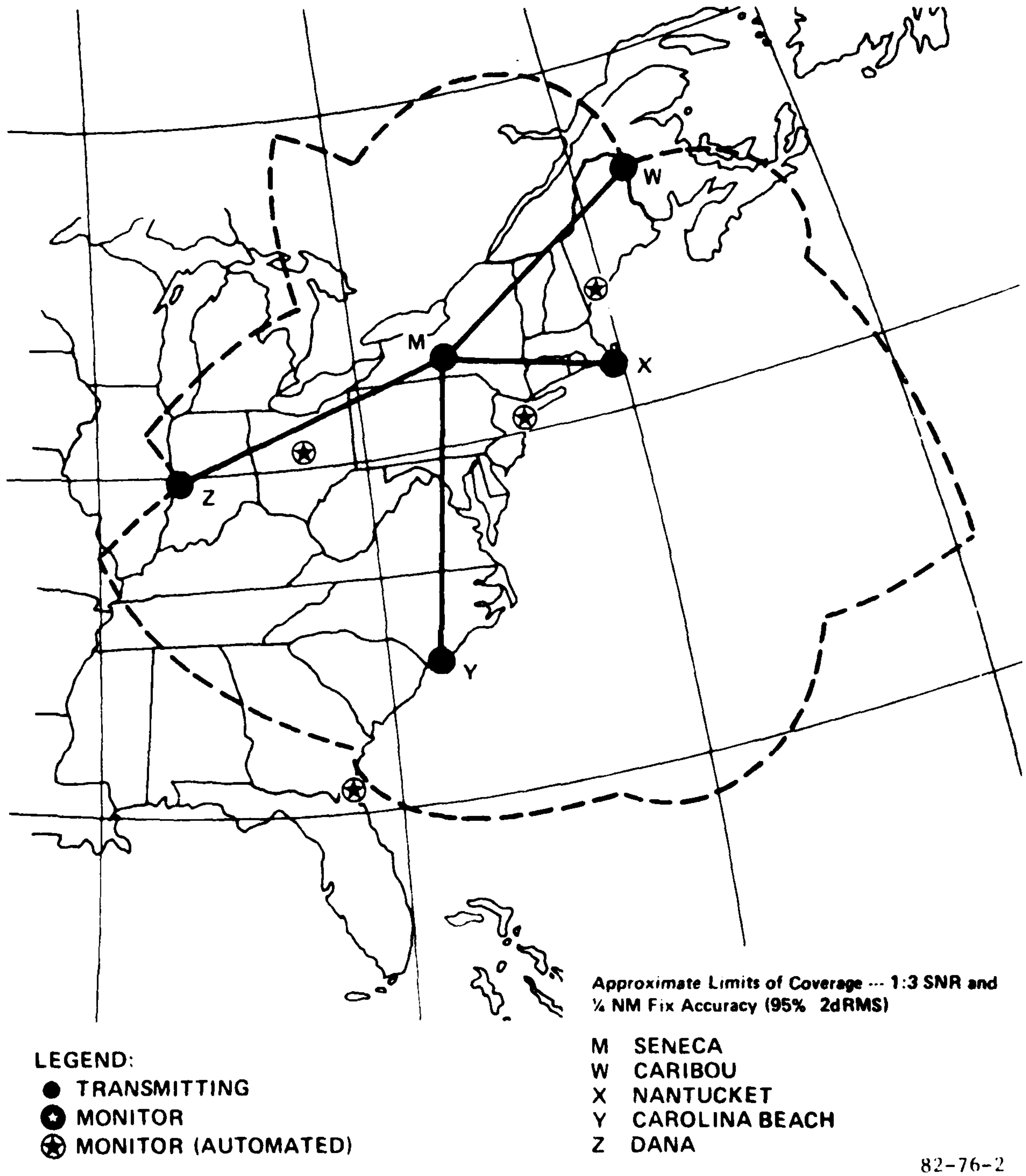

FIGURE 2. NORTHEAST U.S. LORAN-C CHAIN

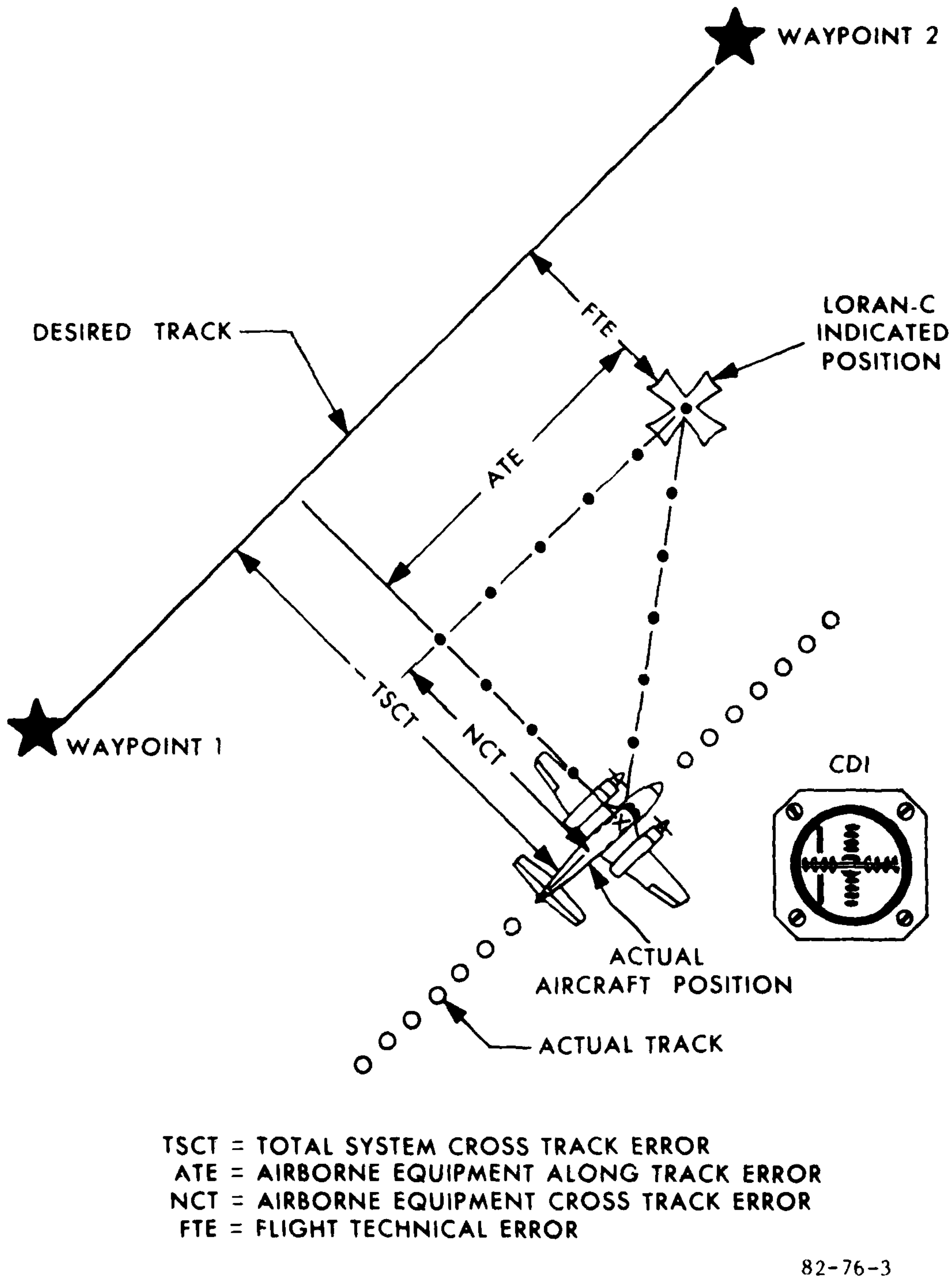

FIGURE 3. NAVIGATION SYSTEM ERROR TERMS

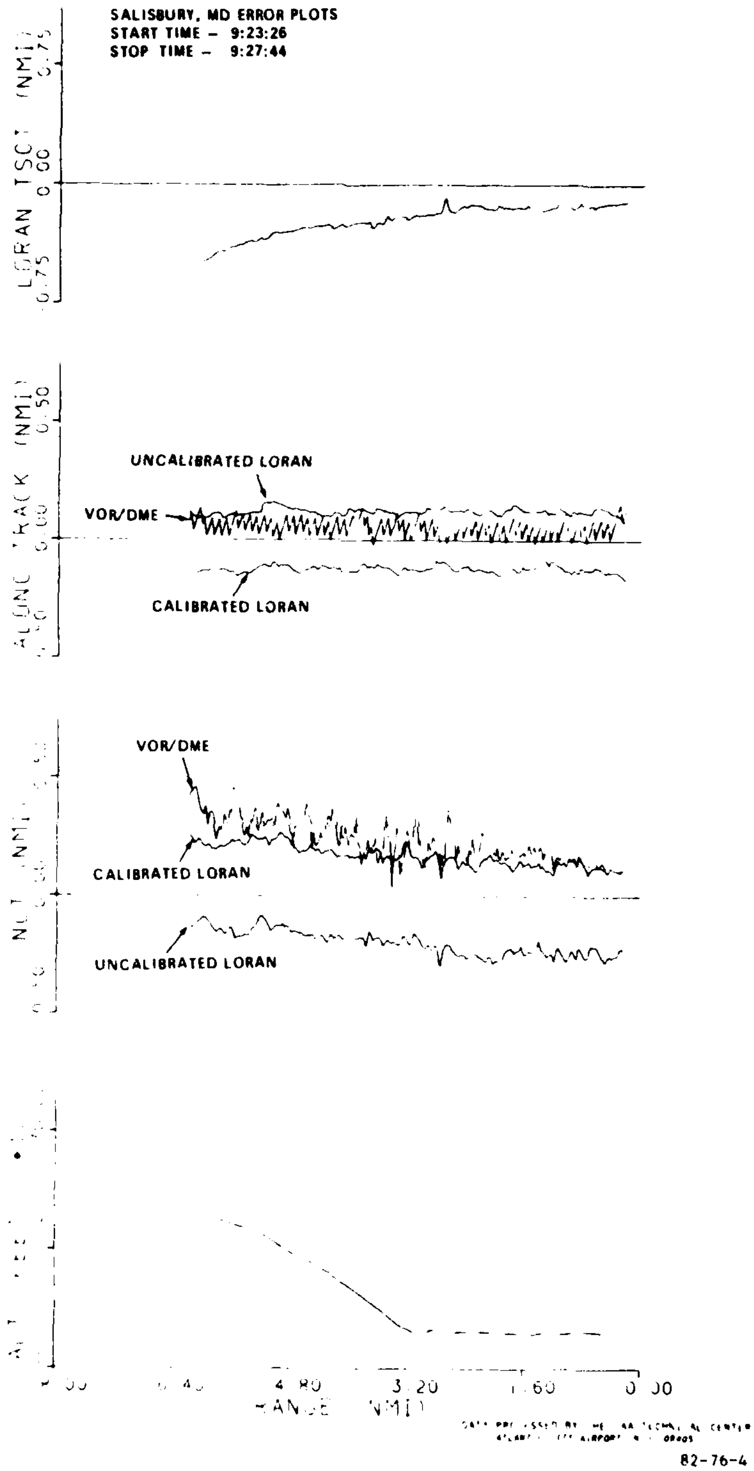

FIGURE 4. SALISBURY, REPRESENTATIVE PLOT

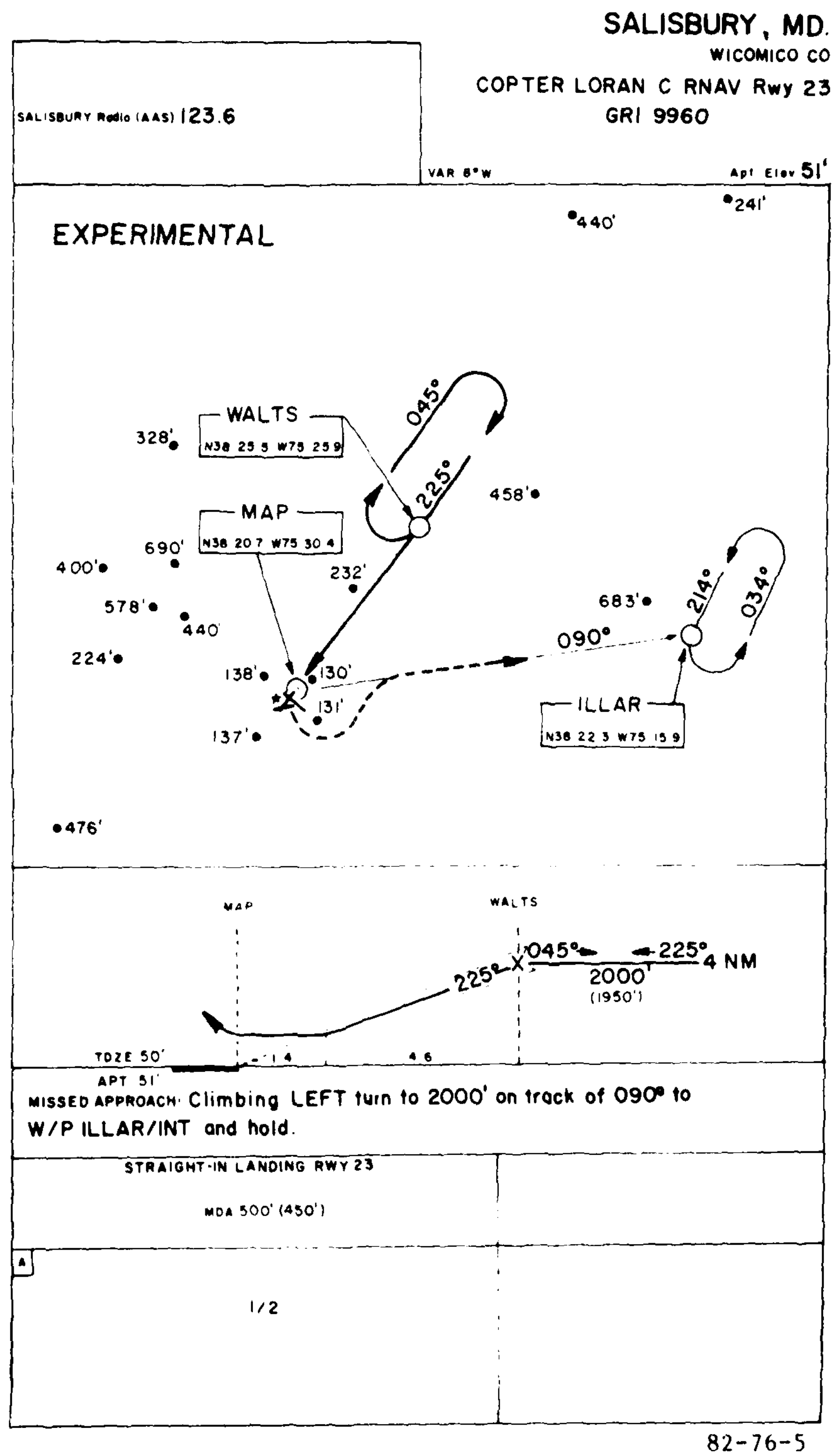

FIGURE 5. SALISBURY APPROACH

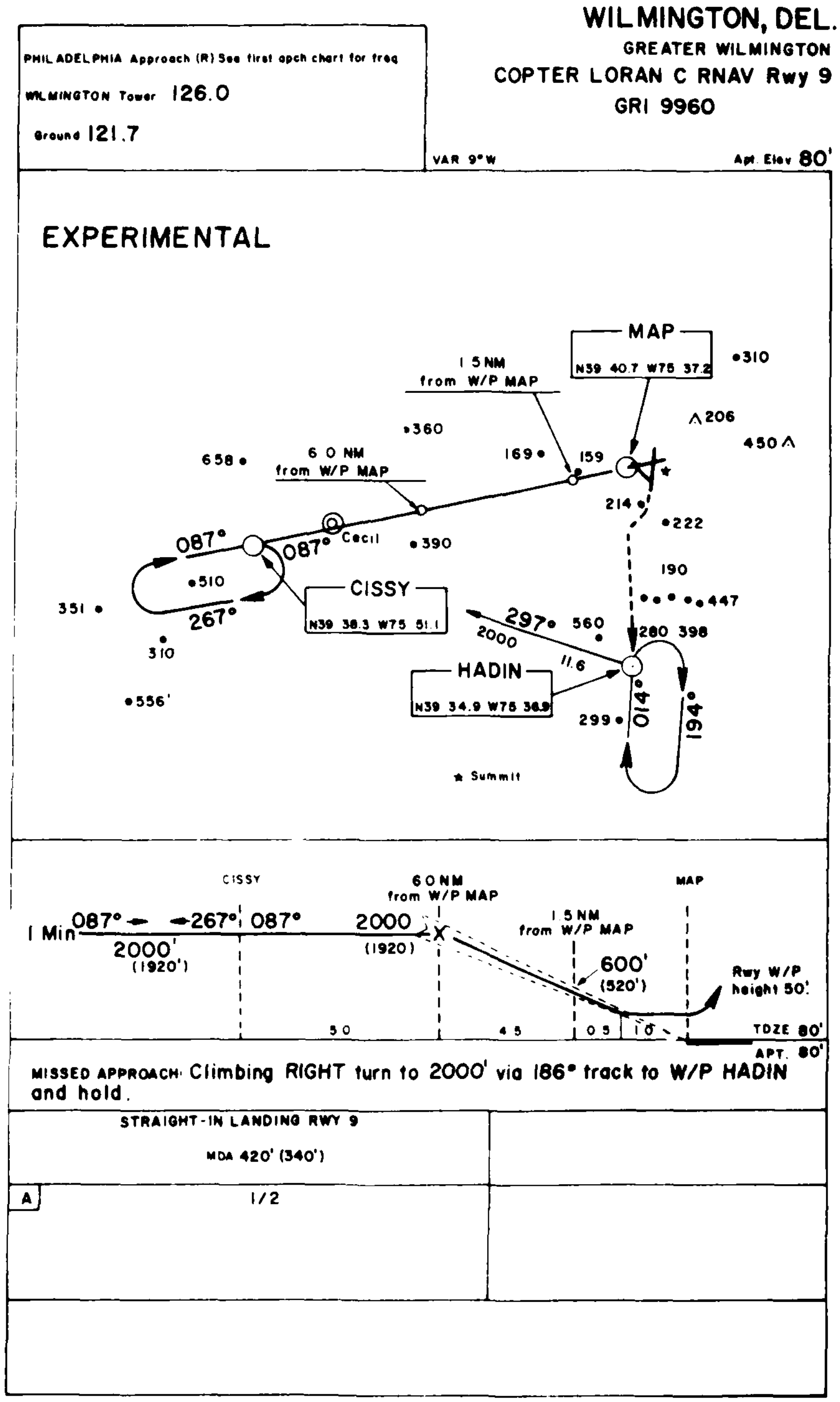

FIGURE 6. WILMINGTON APPROACH

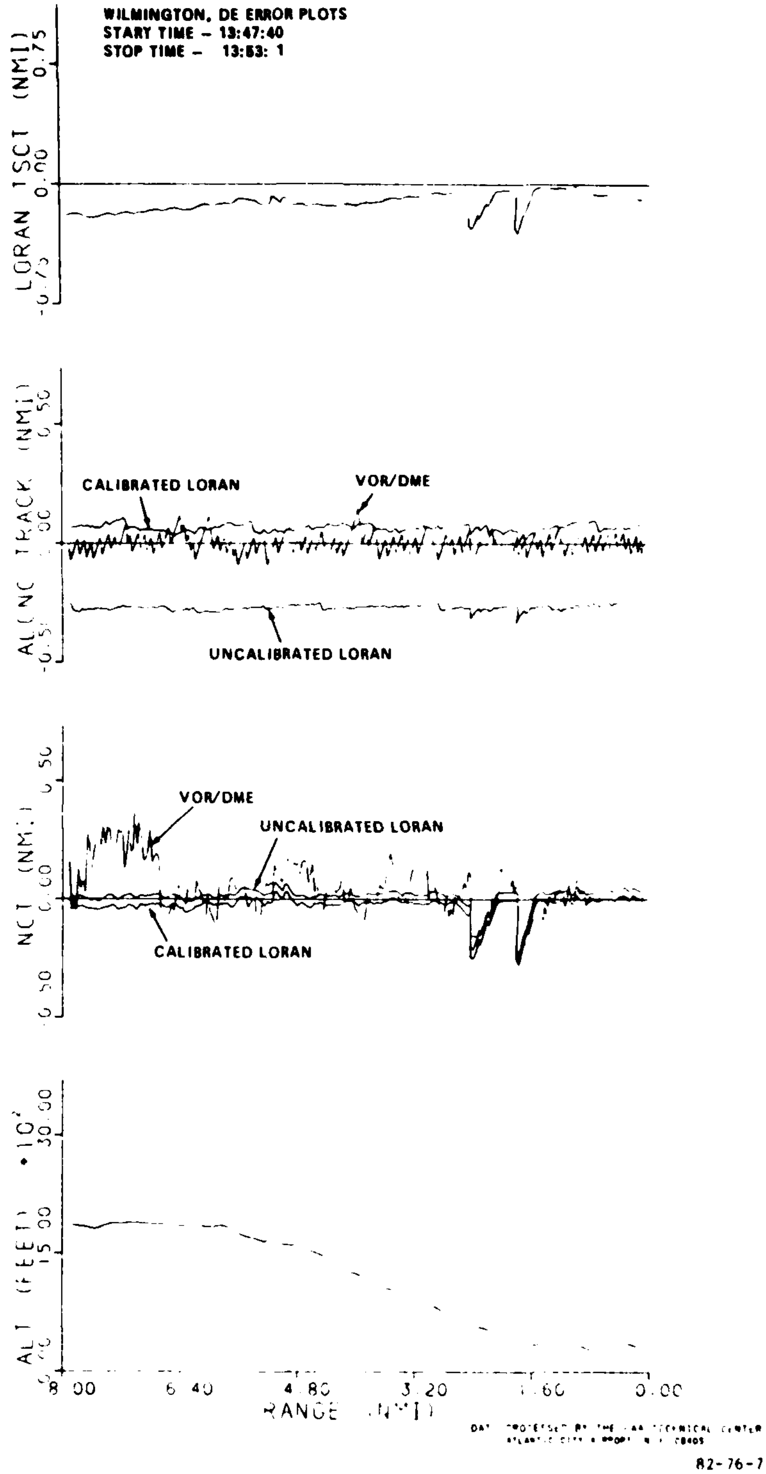

FIGURE 7. WILMINGTON, REPRESENTATIVE PLOT

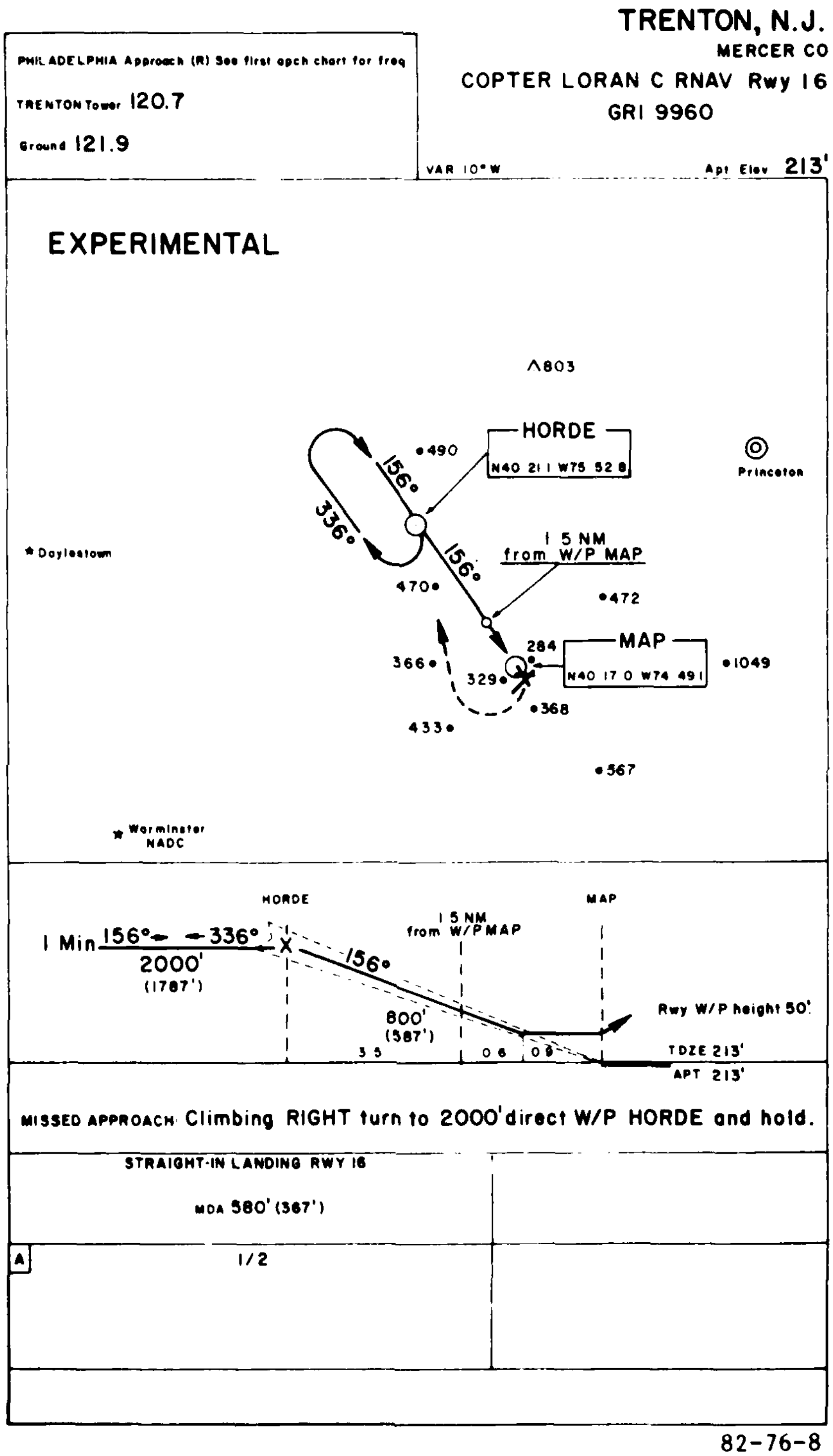

FIGURE 8. TRENTON APPROACH

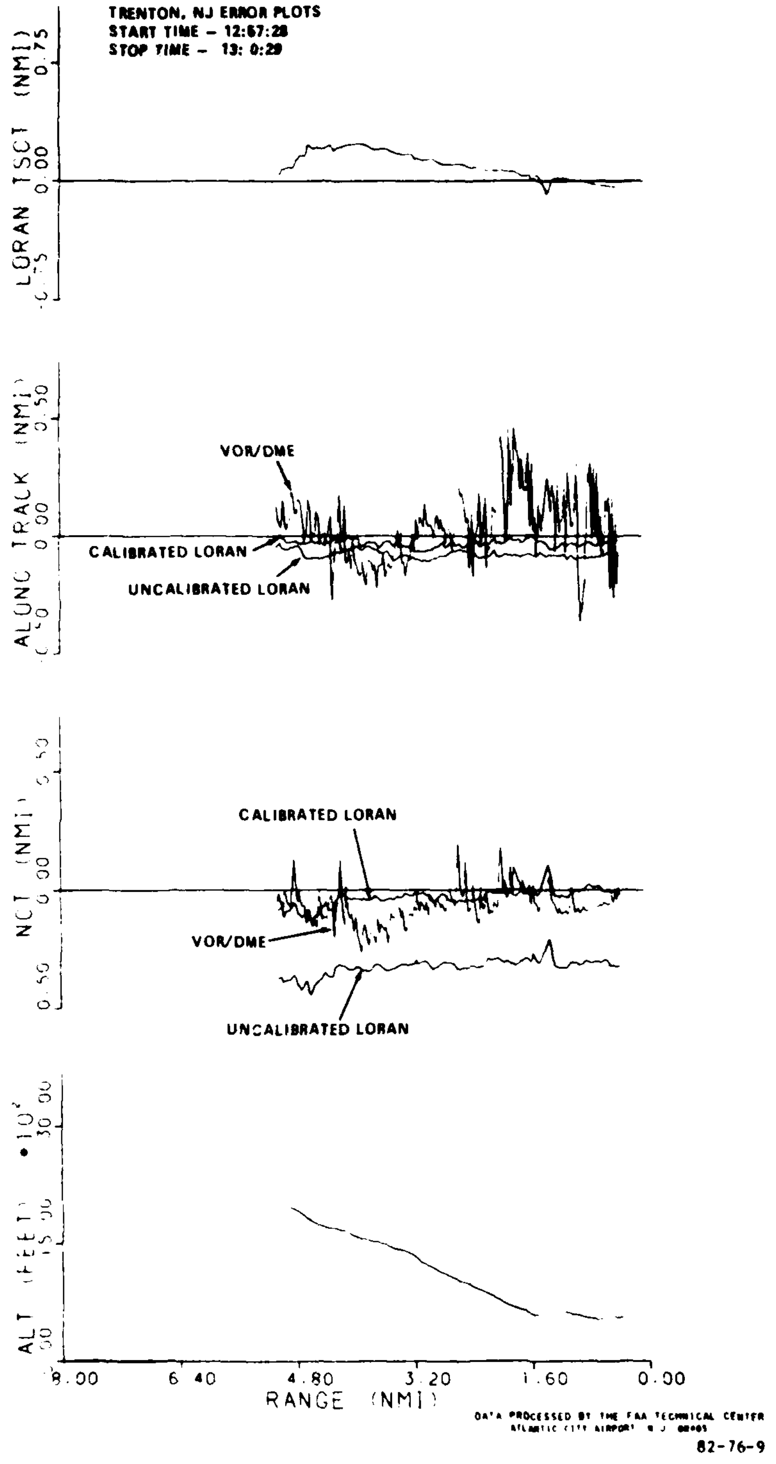

FIGURE 9. TRENTON, REPRESENTATIVE PLOT

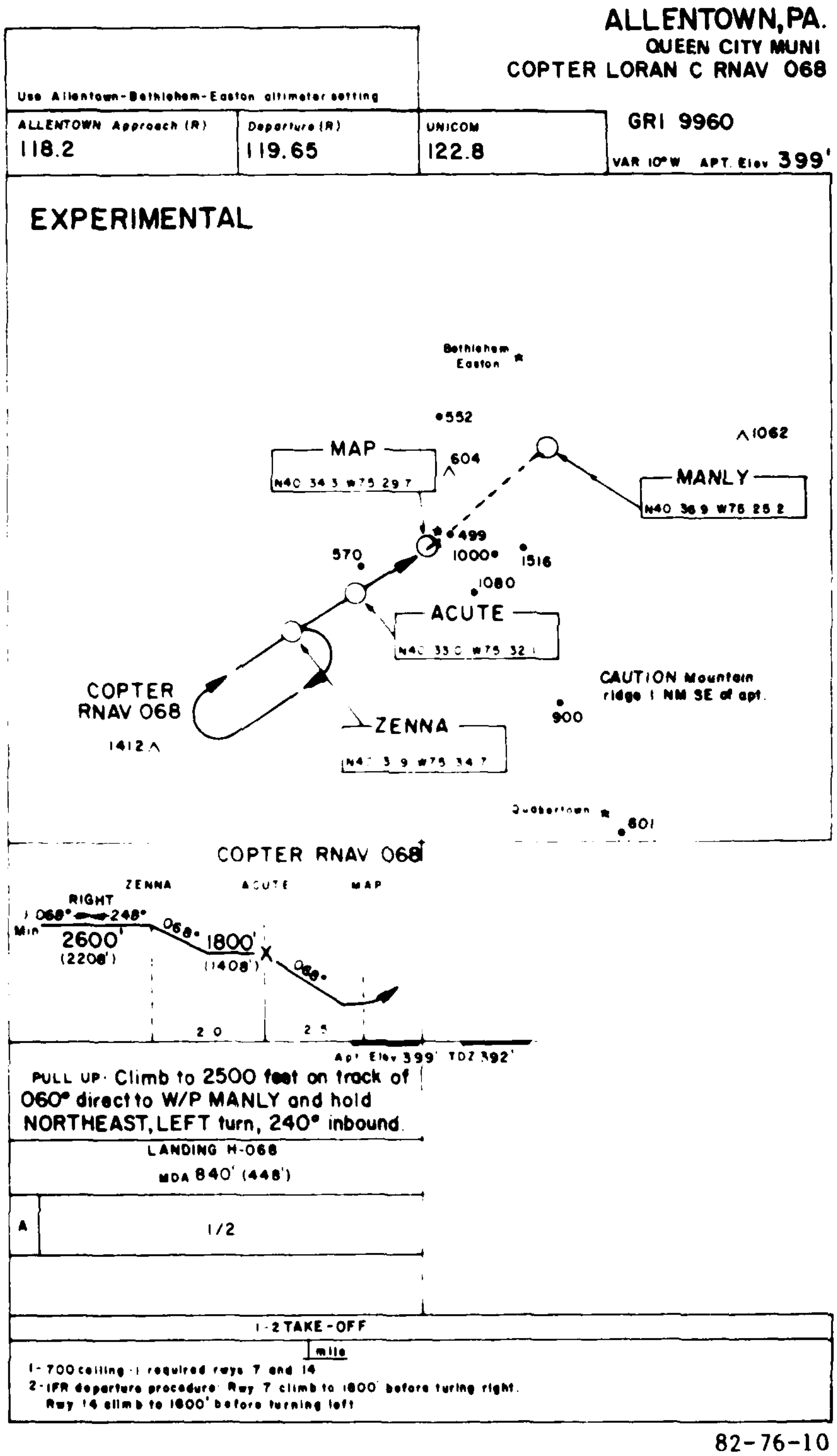

FIGURE 10. ALLENTOWN APPROACH

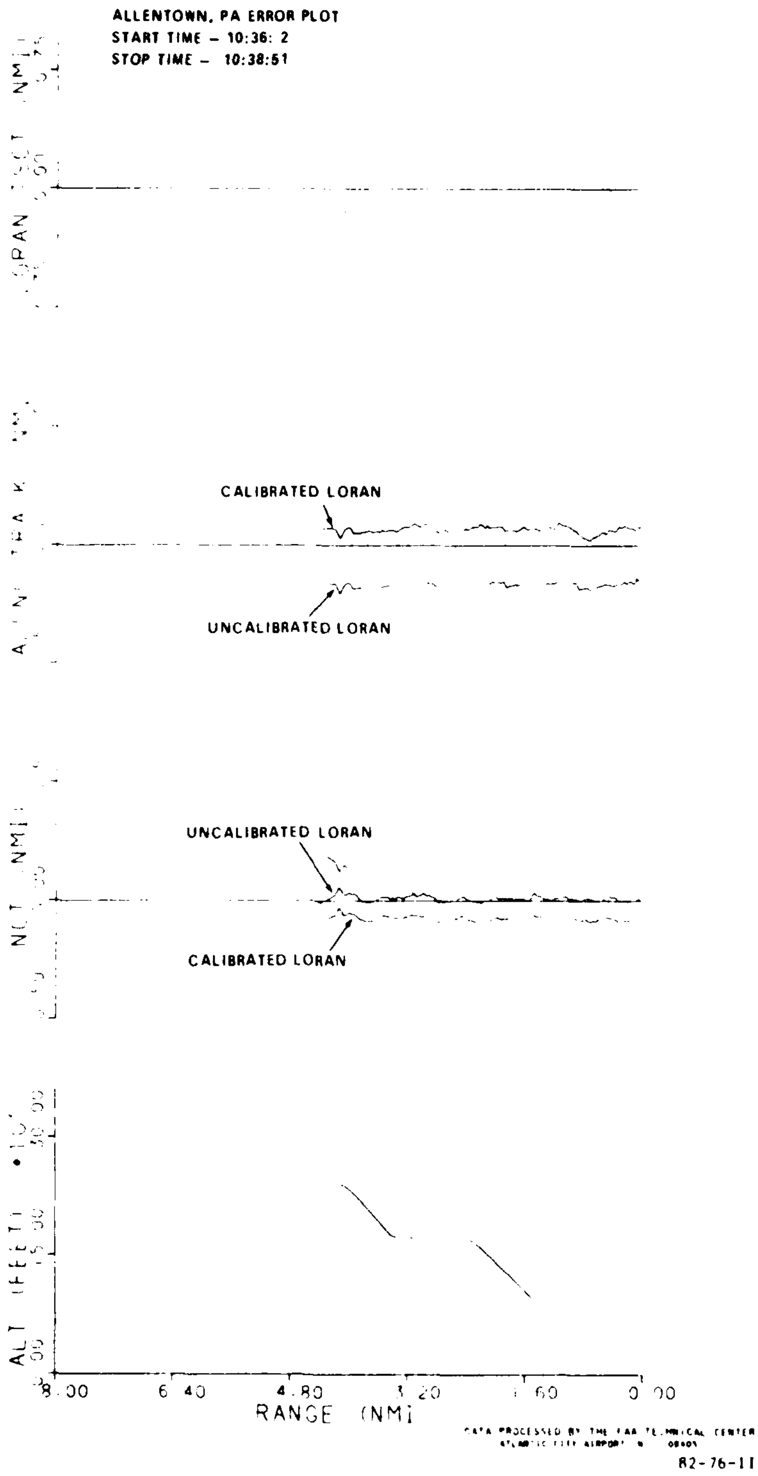

FIGURE 11. ALLENTOWN, REPRESENTATIVE PLOT

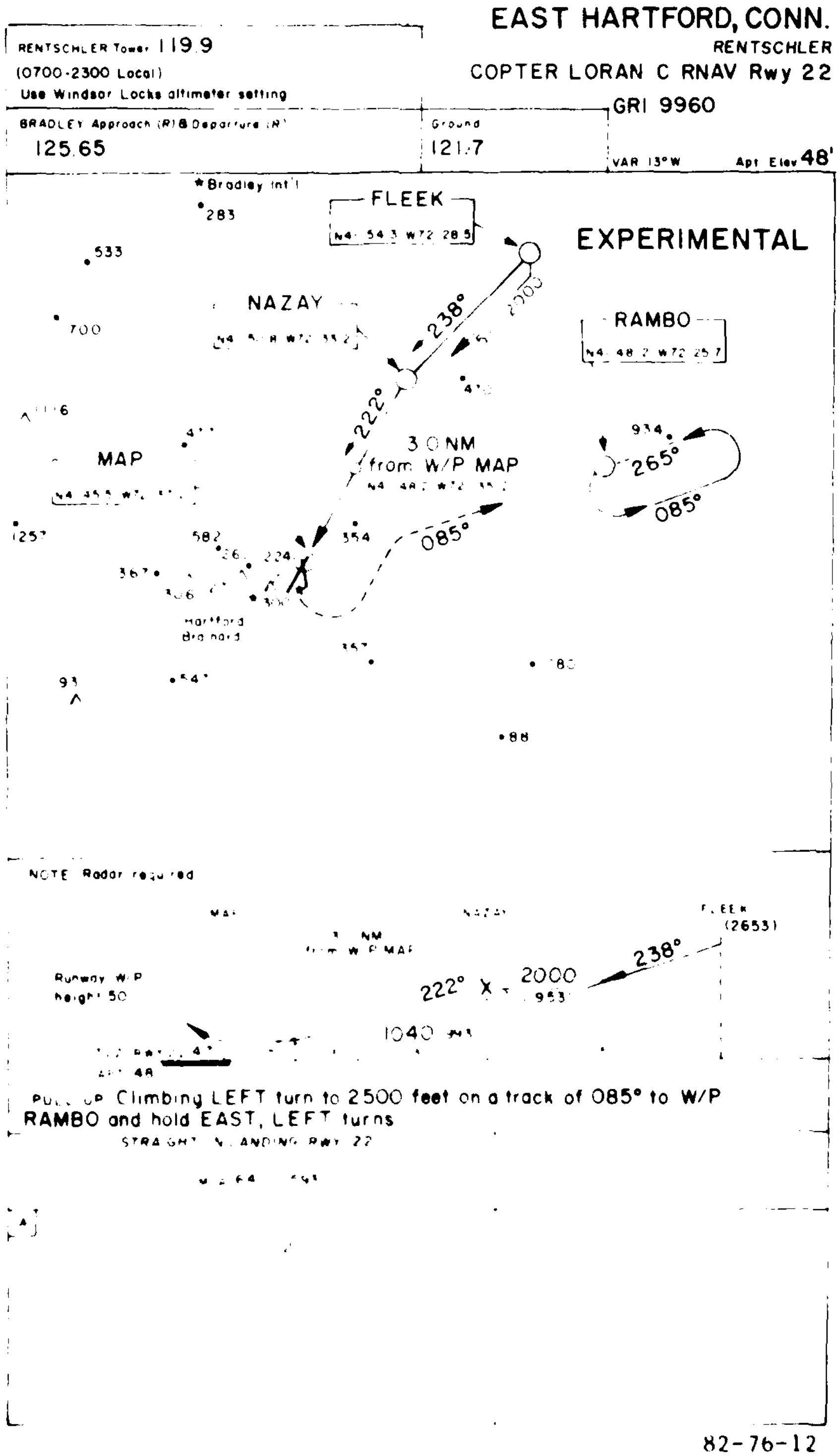

FIGURE 12. HARTFORD APPROACH

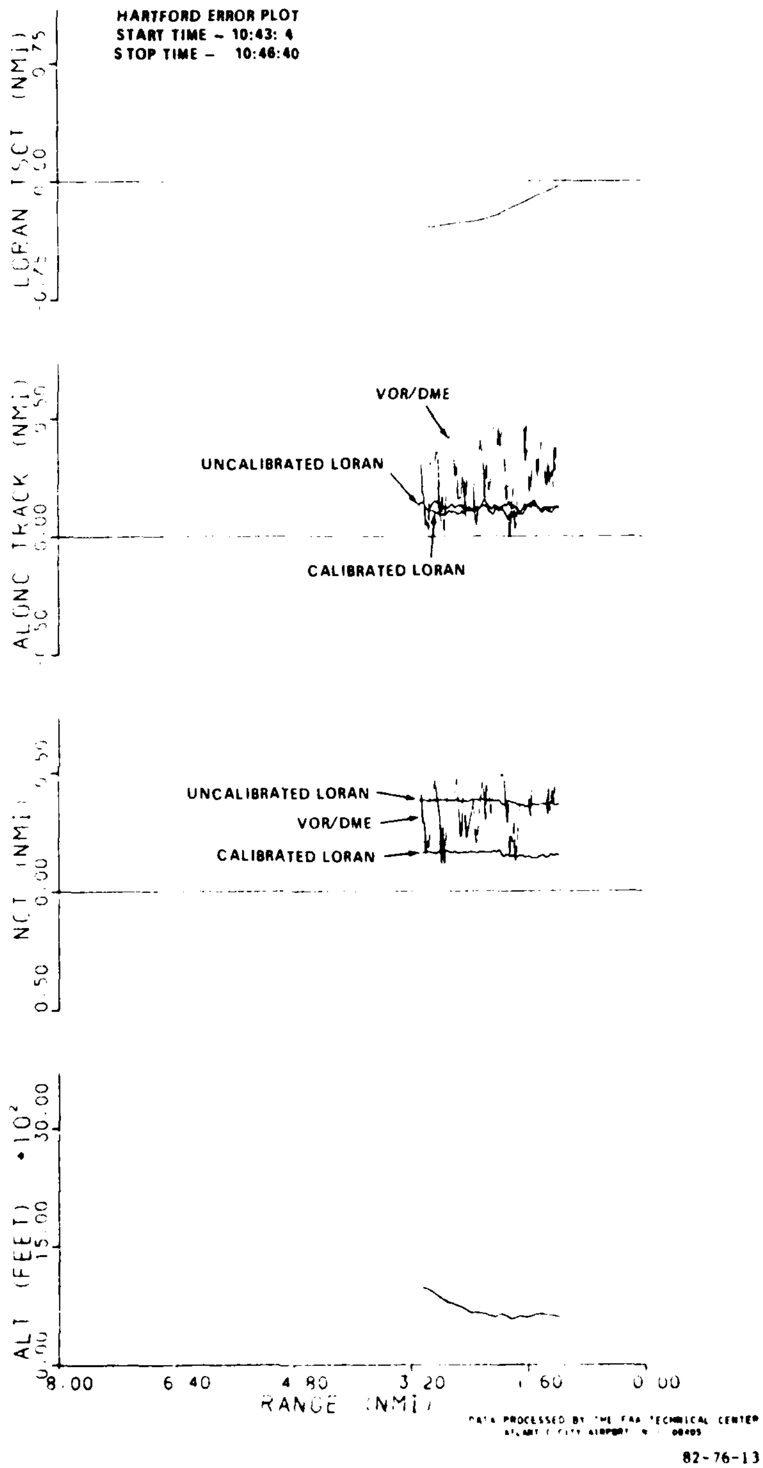

FIGURE 13. HARTFORD, REPRESENTATIVE PLOT

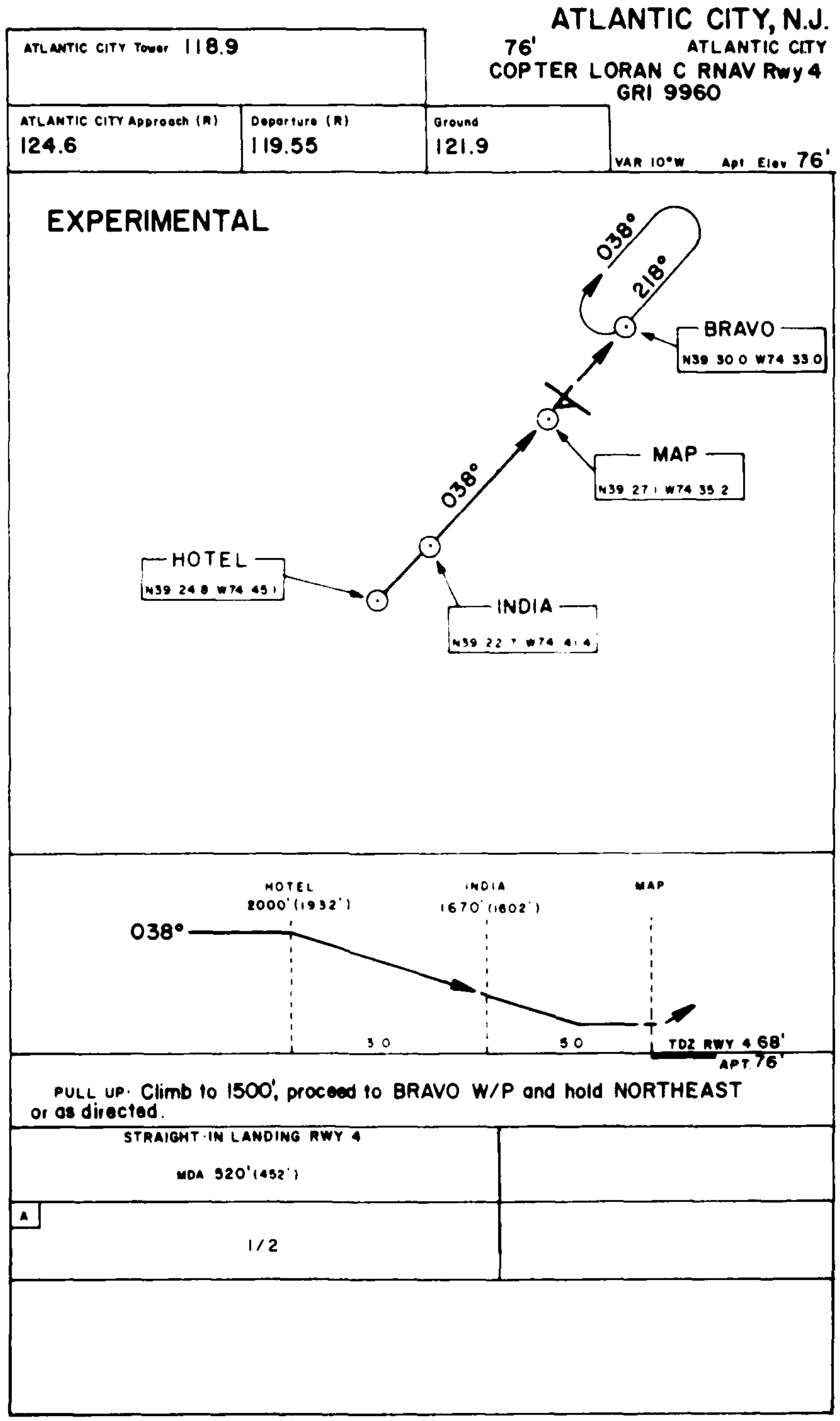

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FIGURE 14. ATLANTIC CITY APPROACH

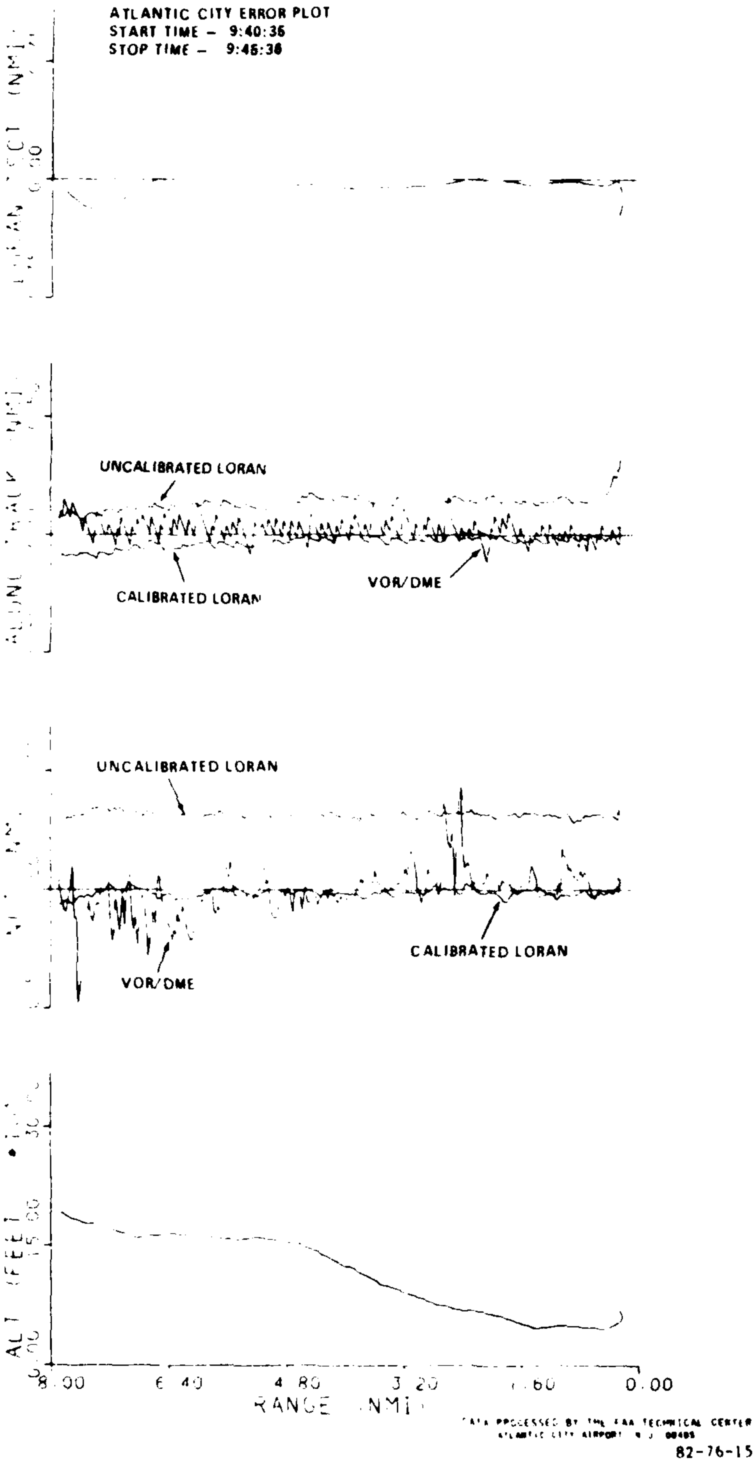


FIGURE 15. ATLANTIC CITY, REPRESENTATIVE PLOT

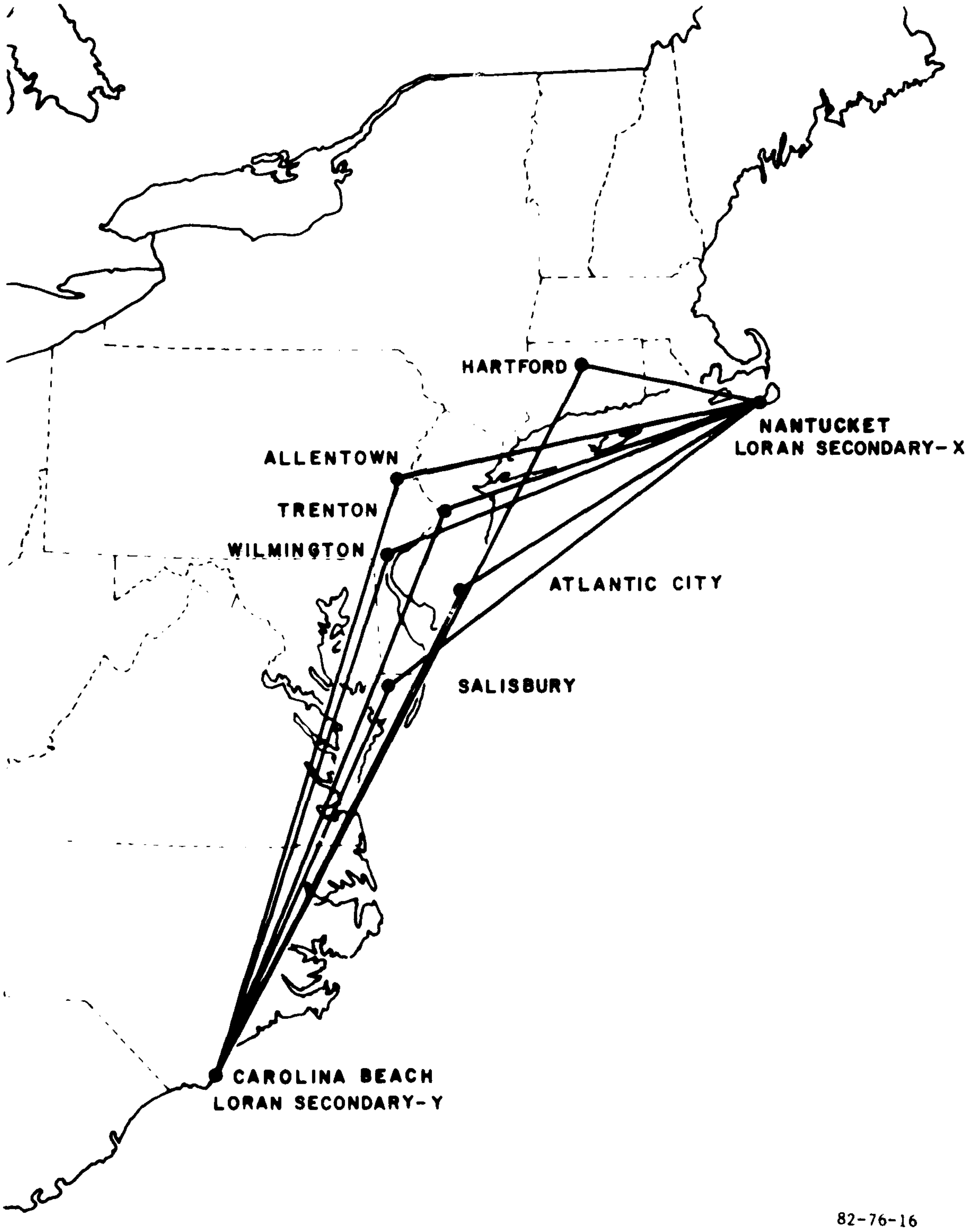
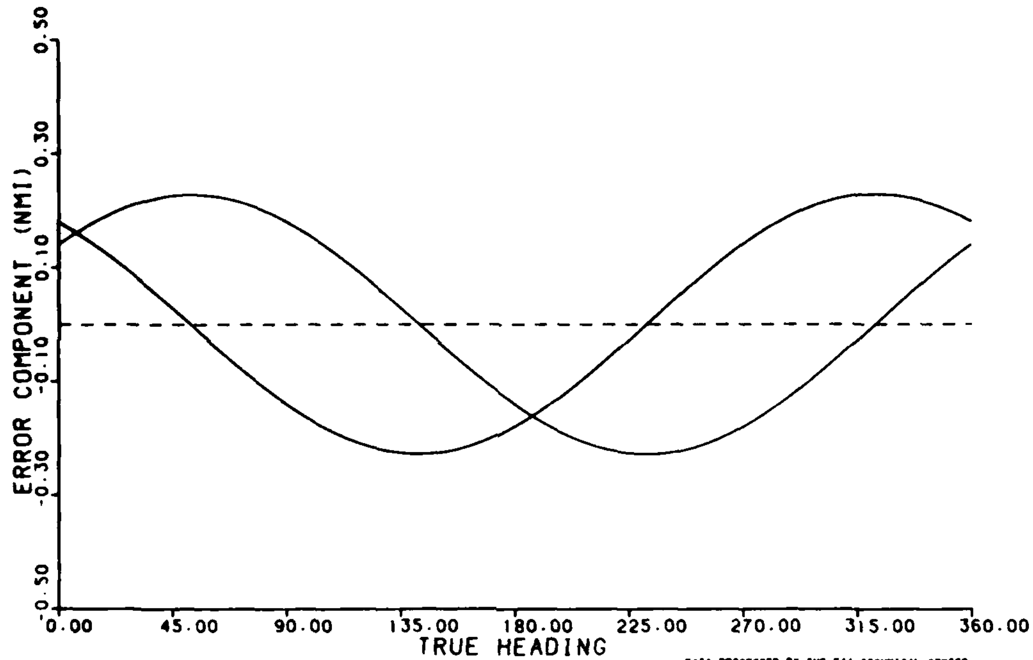


FIGURE 16. RELATIONSHIP OF LORAN TRANSMITTERS TO SUBJECT AIRPORTS

SALISBURY.LOCAL CALIBRATION:ERROR VARIATION WITH HEADING



DATA PROCESSED BY THE FAA TECHNICAL CENTER
ATLANTIC CITY AIRPORT, N.J. 08405

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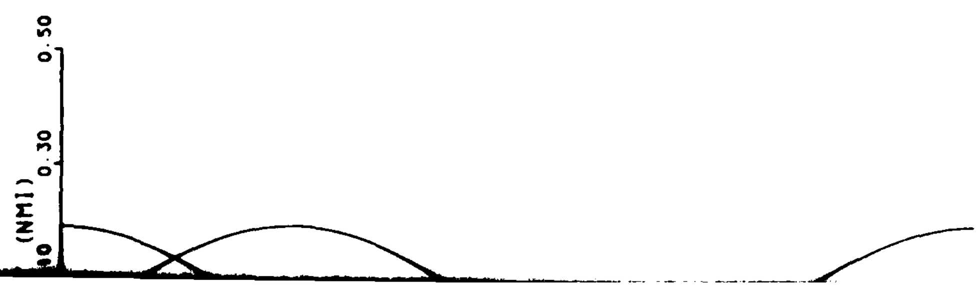
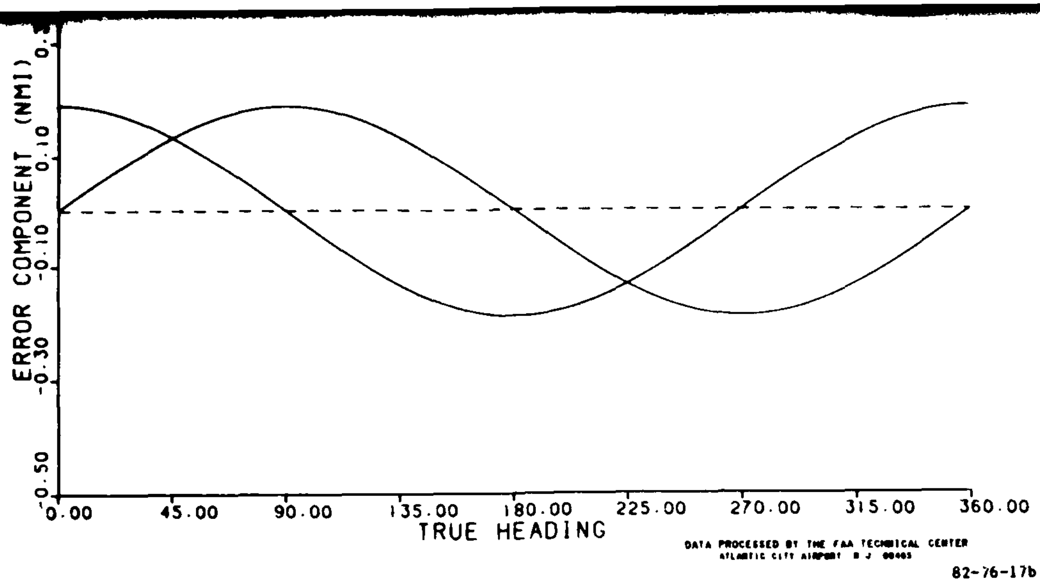
SALISBURY.ACY CALIBRATION:ERROR VARIATION WITH HEADING





SALISBURY.UNCALIBRATED.ERROR VARIATION WITH HEADING

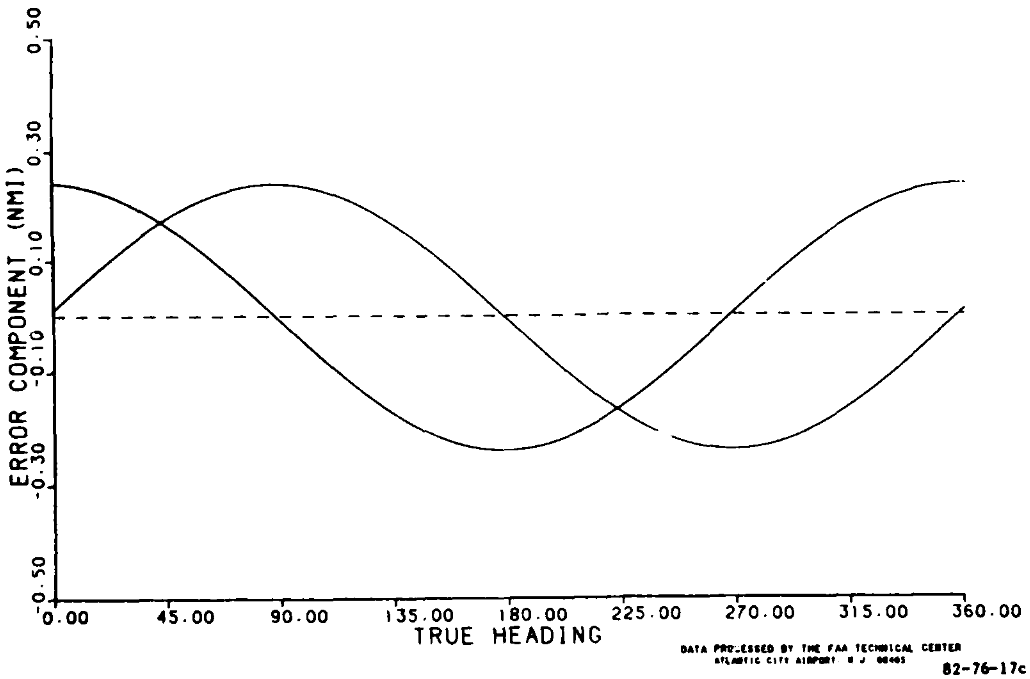
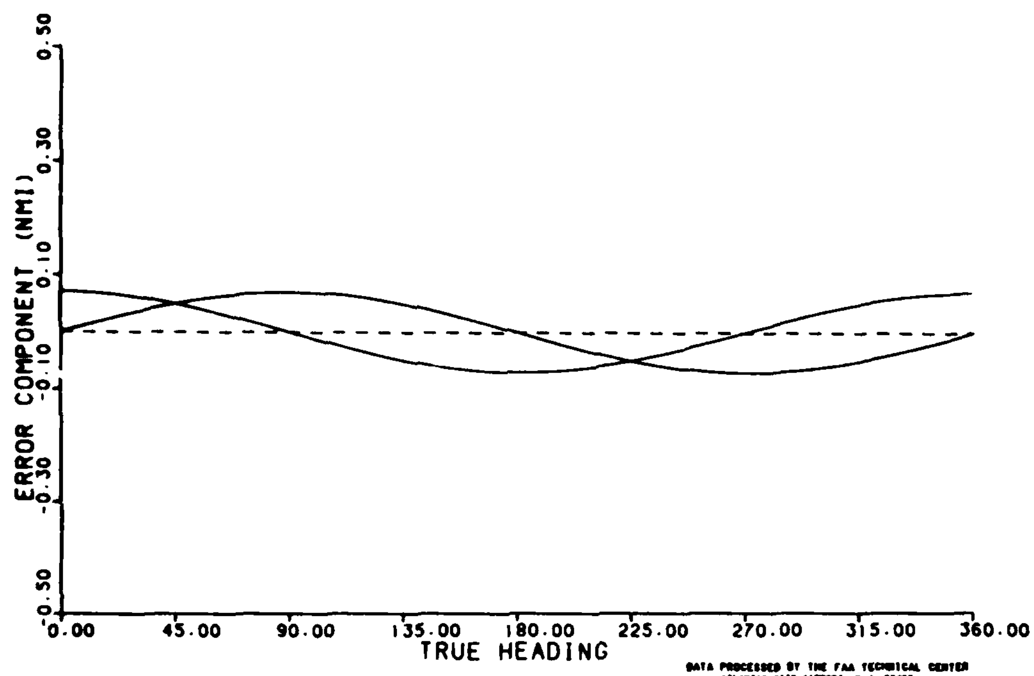


FIGURE 17. SALISBURY, LORAN ERROR VARIATION WITH HEADING

1

2

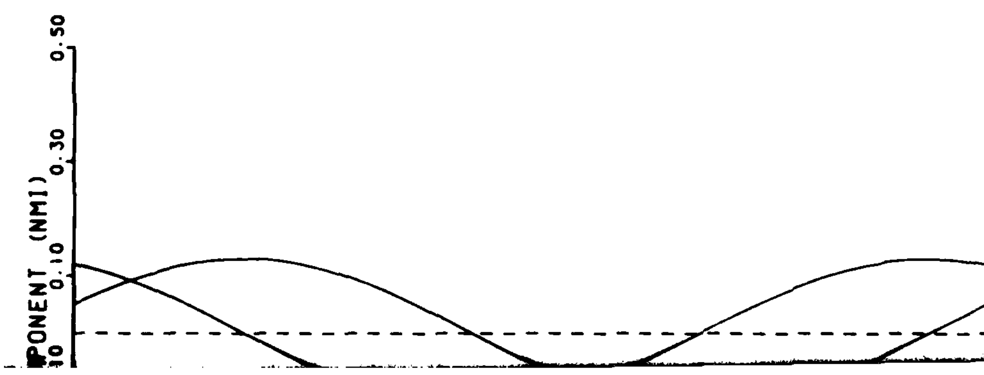
WILMINGTON.LOCAL CALIBRARION:ERROR VARIATION WITH HEADING

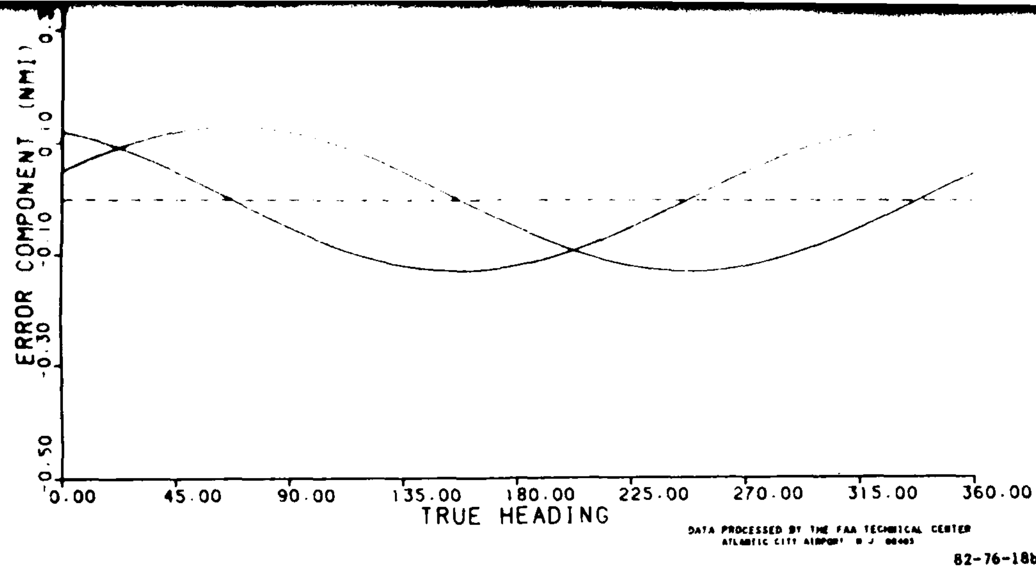


DATA PROCESSED BY THE FAA TECHNICAL CENTER ATLANTIC CITY AIRPORT, N.J. 08405

82-76-18a

WILMINGTON.ACY CALIBRATION:ERROR VARIATION WITH HEADING





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WILMINGTON.UNCALIBRATED.ERROR VARIATION WITH HEADING

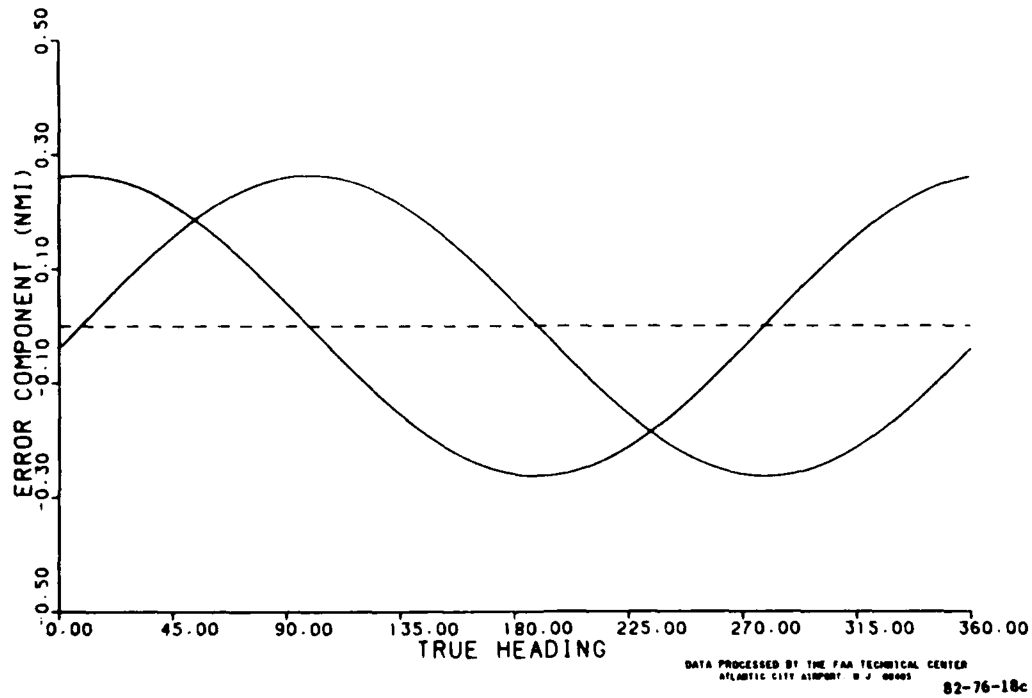

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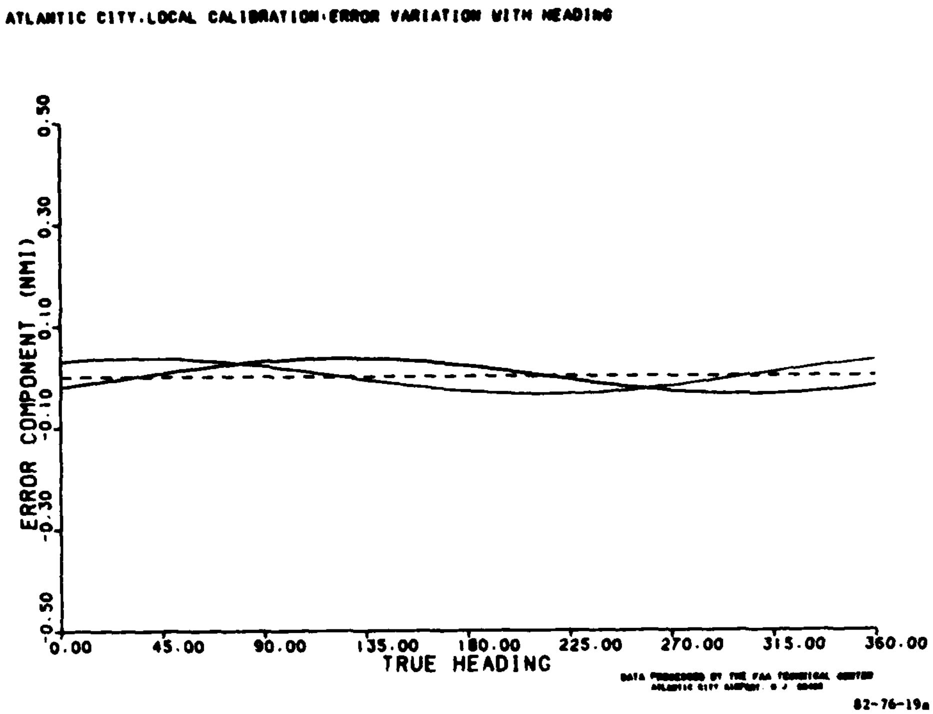
FIGURE 18. WILMINGTON, LORAN ERROR VARIATION WITH HEADING



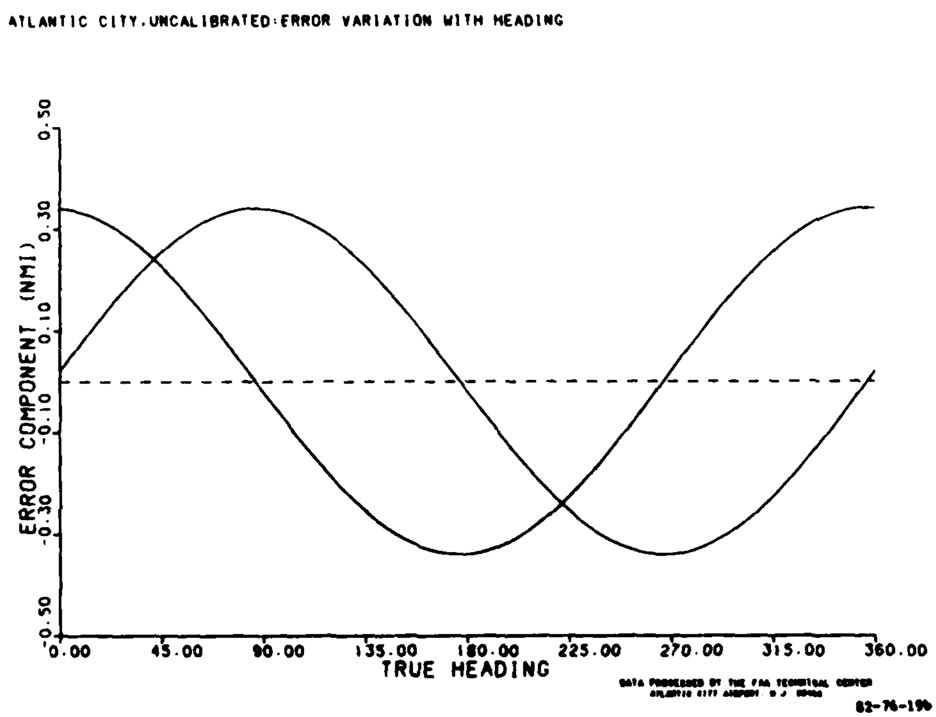
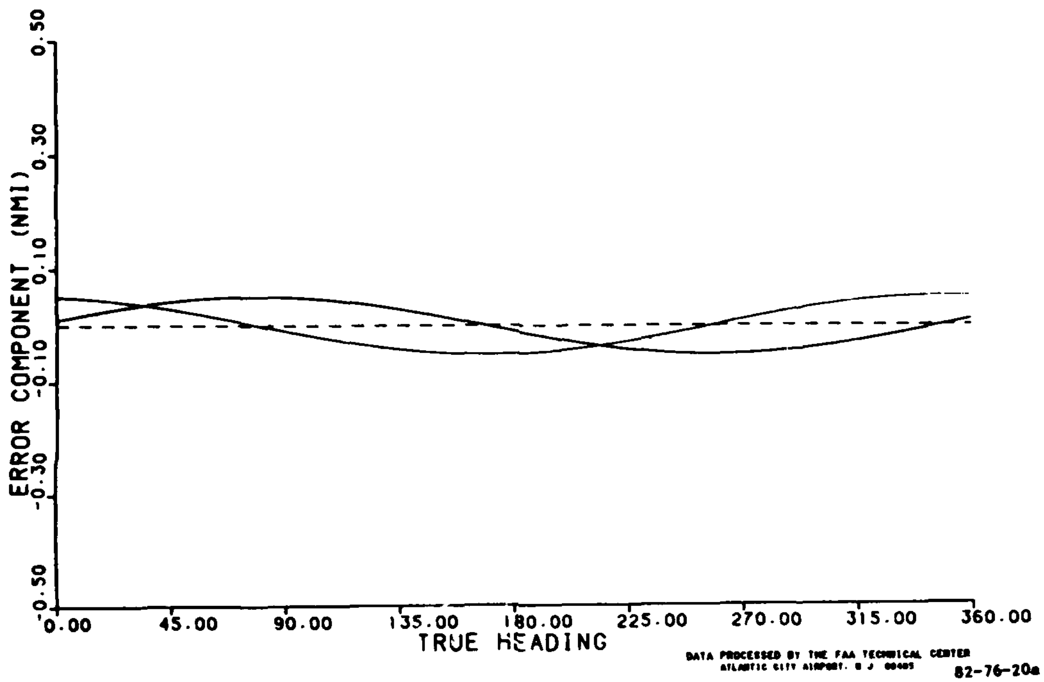
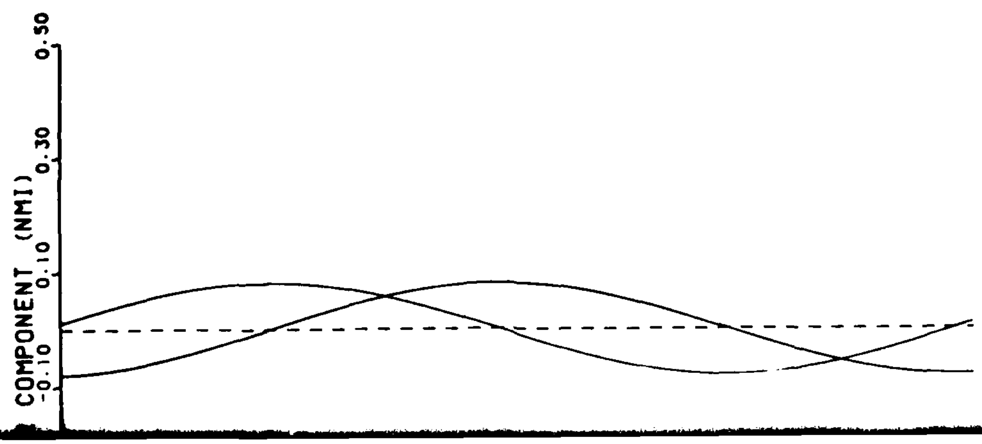


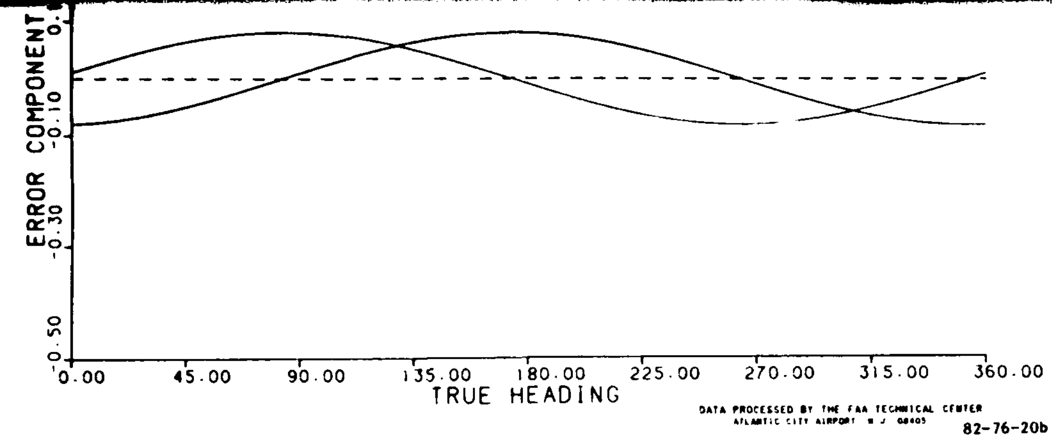
FIGURE 19. ATLANTIC CITY, LORAN ERROR VARIATION WITH HEADING

TRENTON.LOCAL CALIBRATION:ERROR VARIATION WITH HEADING



TRENTON.ACY CALIBRATION:ERROR VARIATION WITH HEADING





TRENTON.UNCALIBRATED ERROR VARIATION WITH HEADING

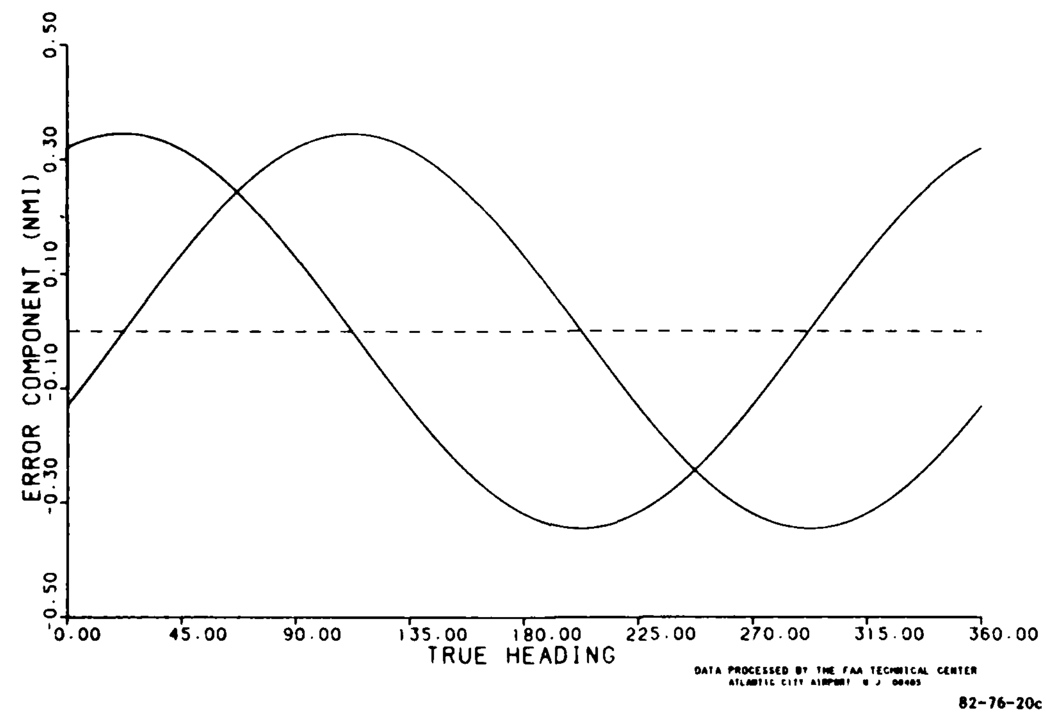
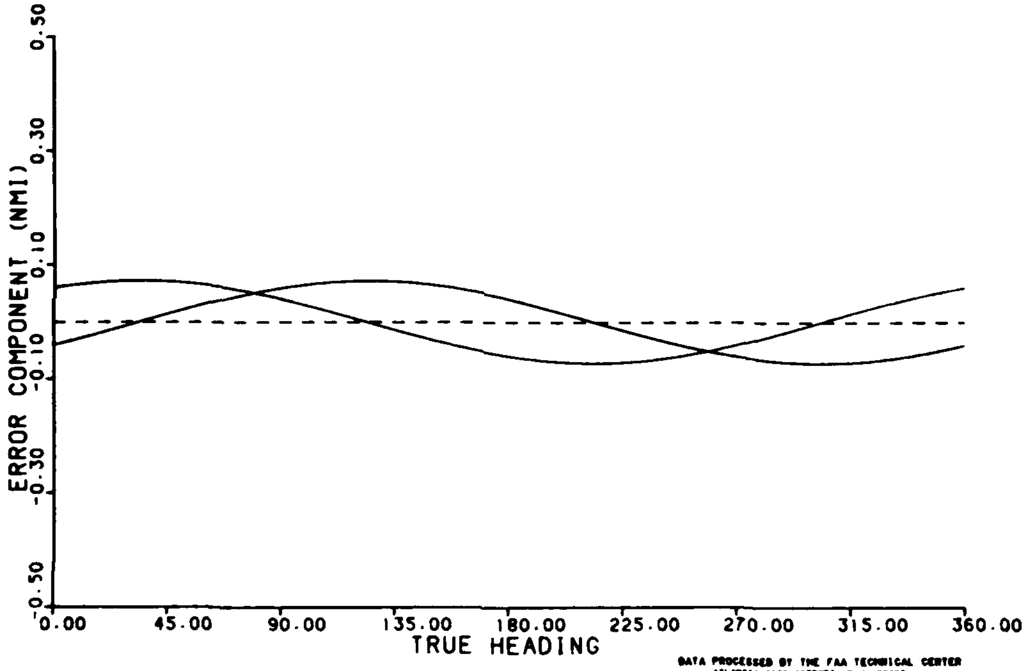


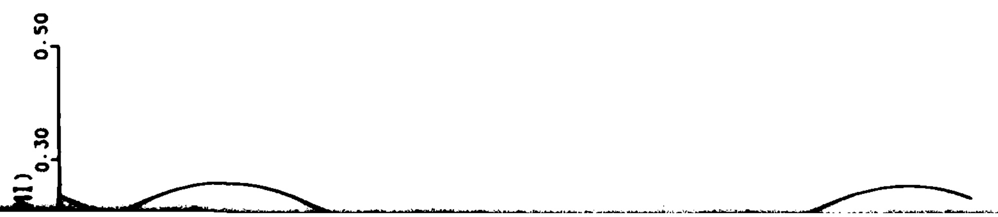
FIGURE 20. TRENTON, LORAN ERROR VARIATION WITH HEADING

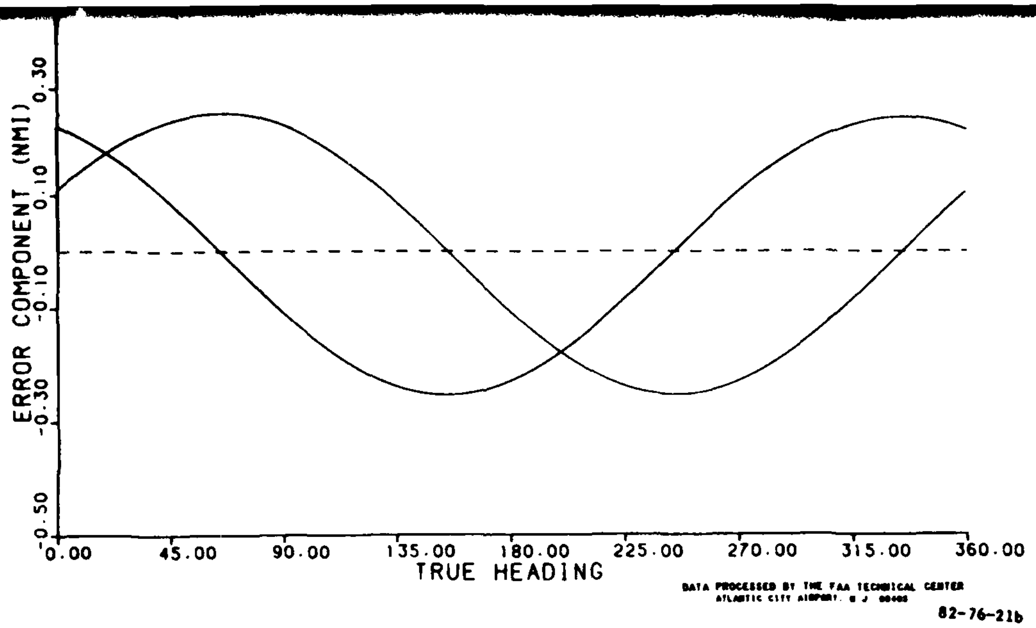
ALLENTOWN.LOCAL CALIBRATION:ERROR VARIATION WITH HEADING



82-76-21a

ALLENTOWN.ACY CALIBRATION:ERROR VARIATION WITH HEADING





ALLENTOWN.UNCALIBRATED:ERROR VARIATION WITH HEADING

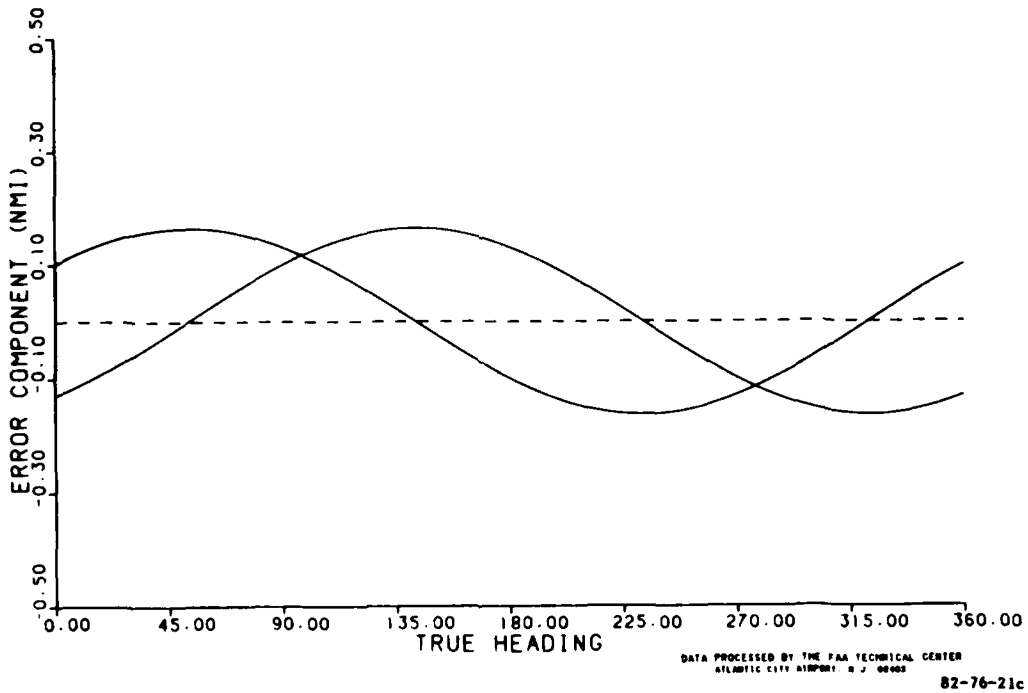
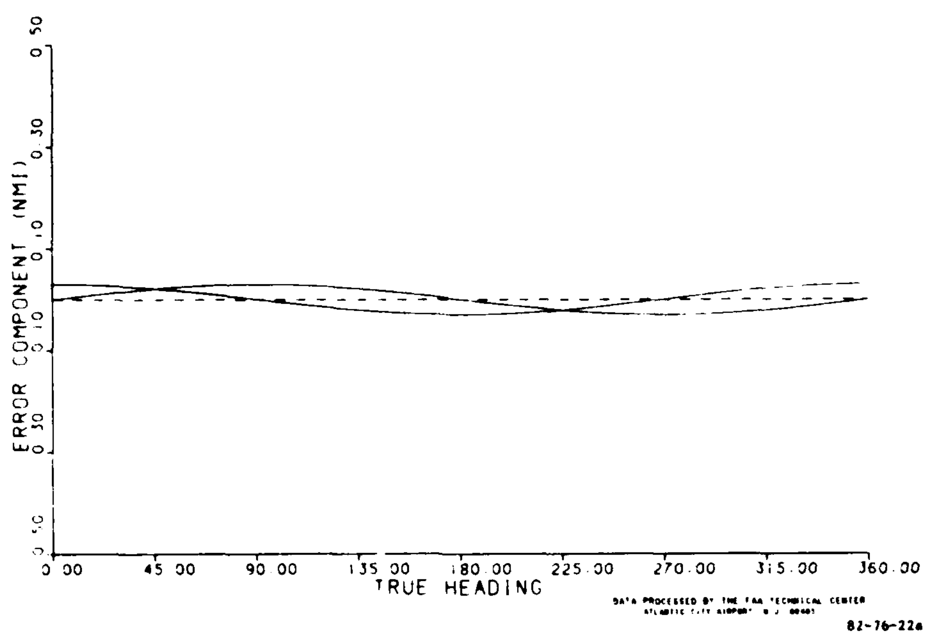


FIGURE 21. ALLLENTOWN, LORAN ERROR VARIATION WITH HEADING

HARTFORD LOCAL CALIBRATION ERROR VARIATION WITH HEADING



HARTFORD UNCALIBRATED ERROR VARIATION WITH HEADING

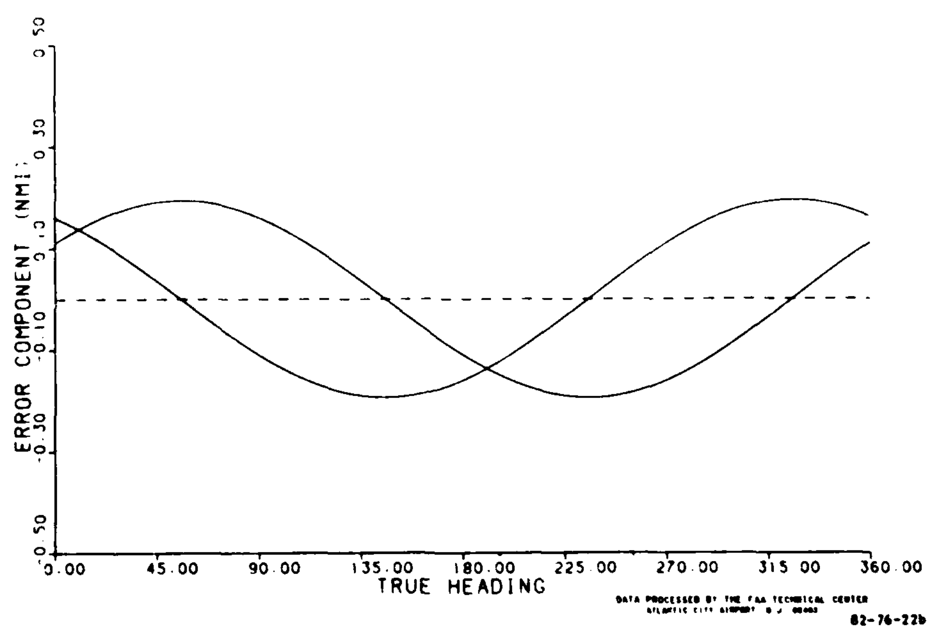


FIGURE 22. HARTFORD, LORAN ERROR VARIATION WITH HEADING

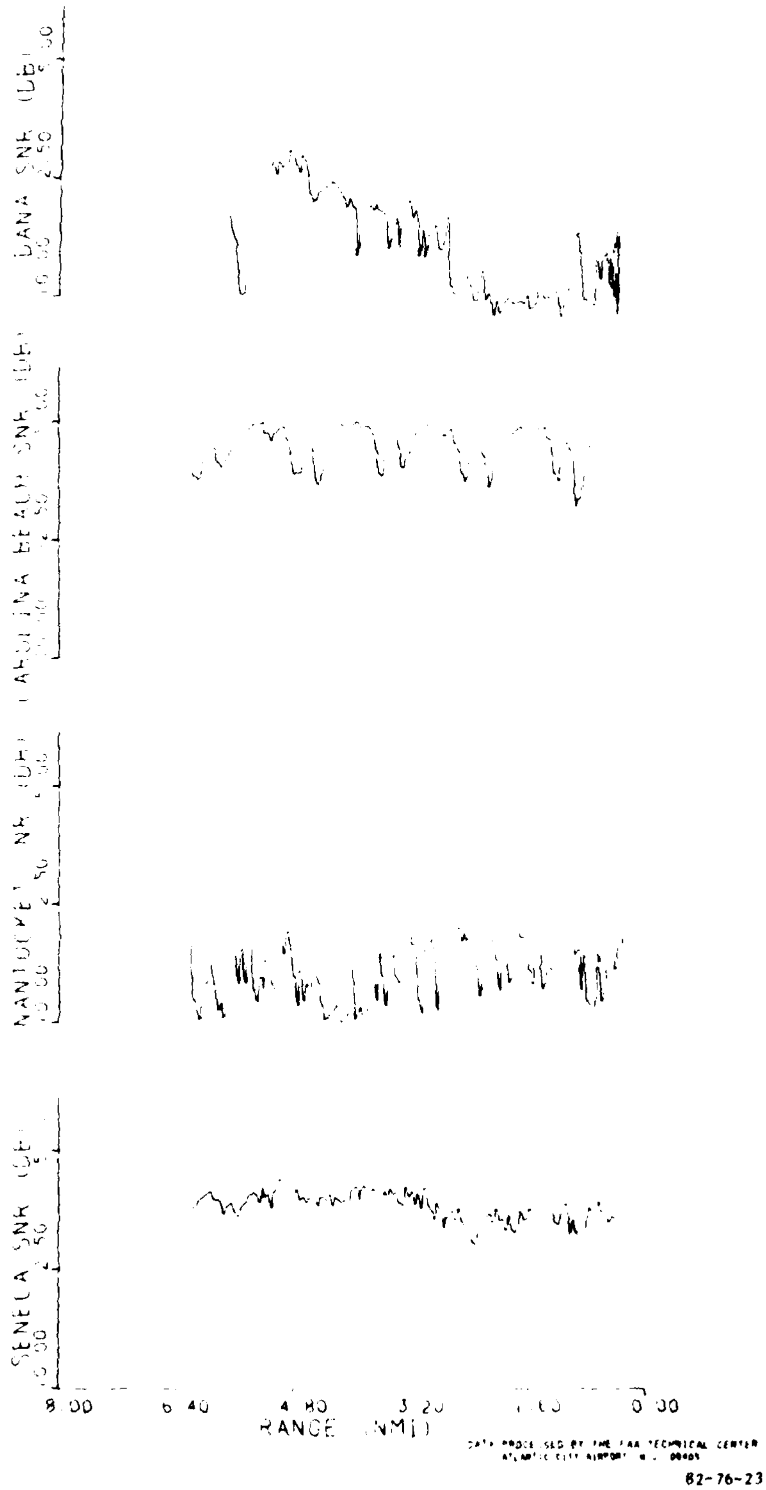


FIGURE 23.   SALISBURY SNR

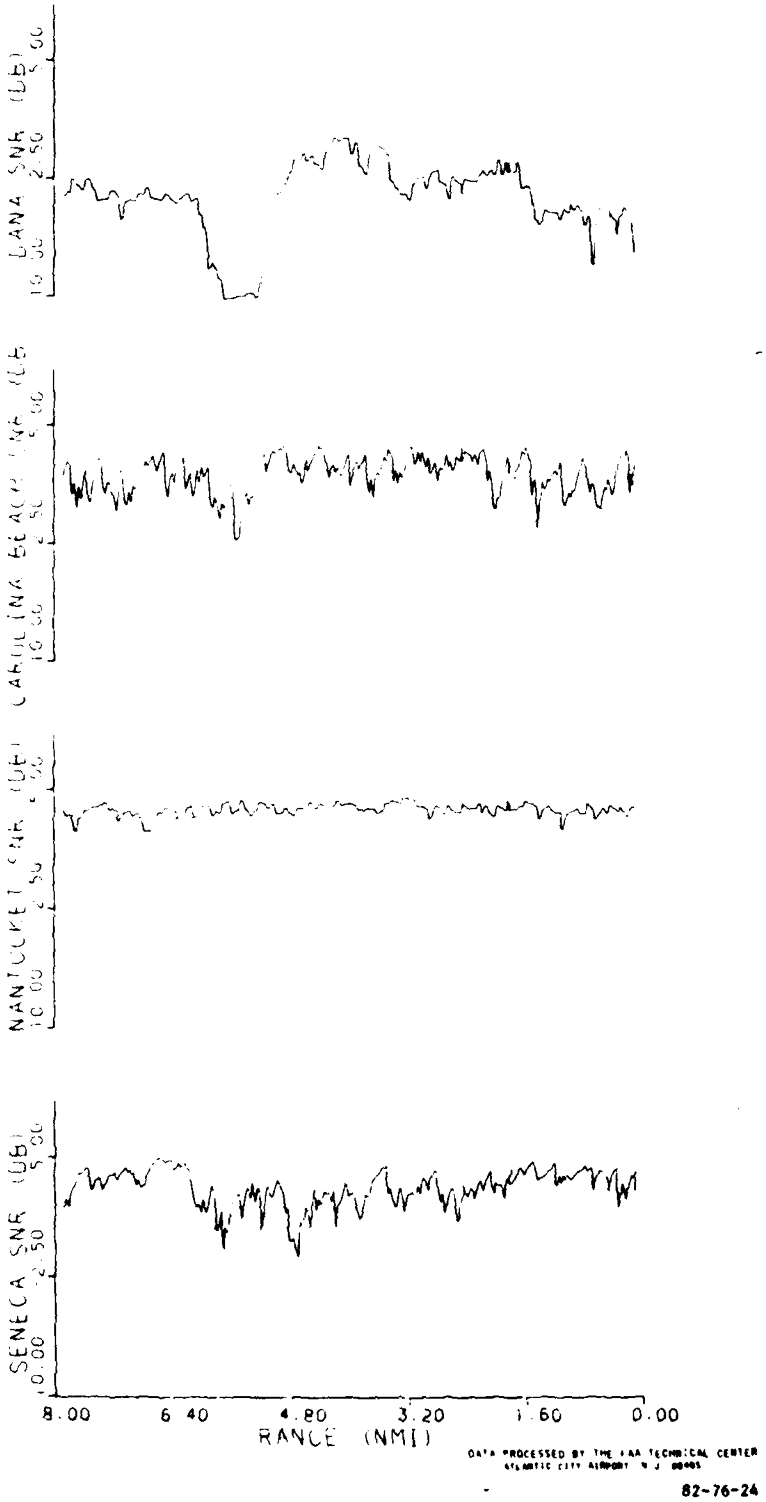


FIGURE 24. WILMINGTON SNR

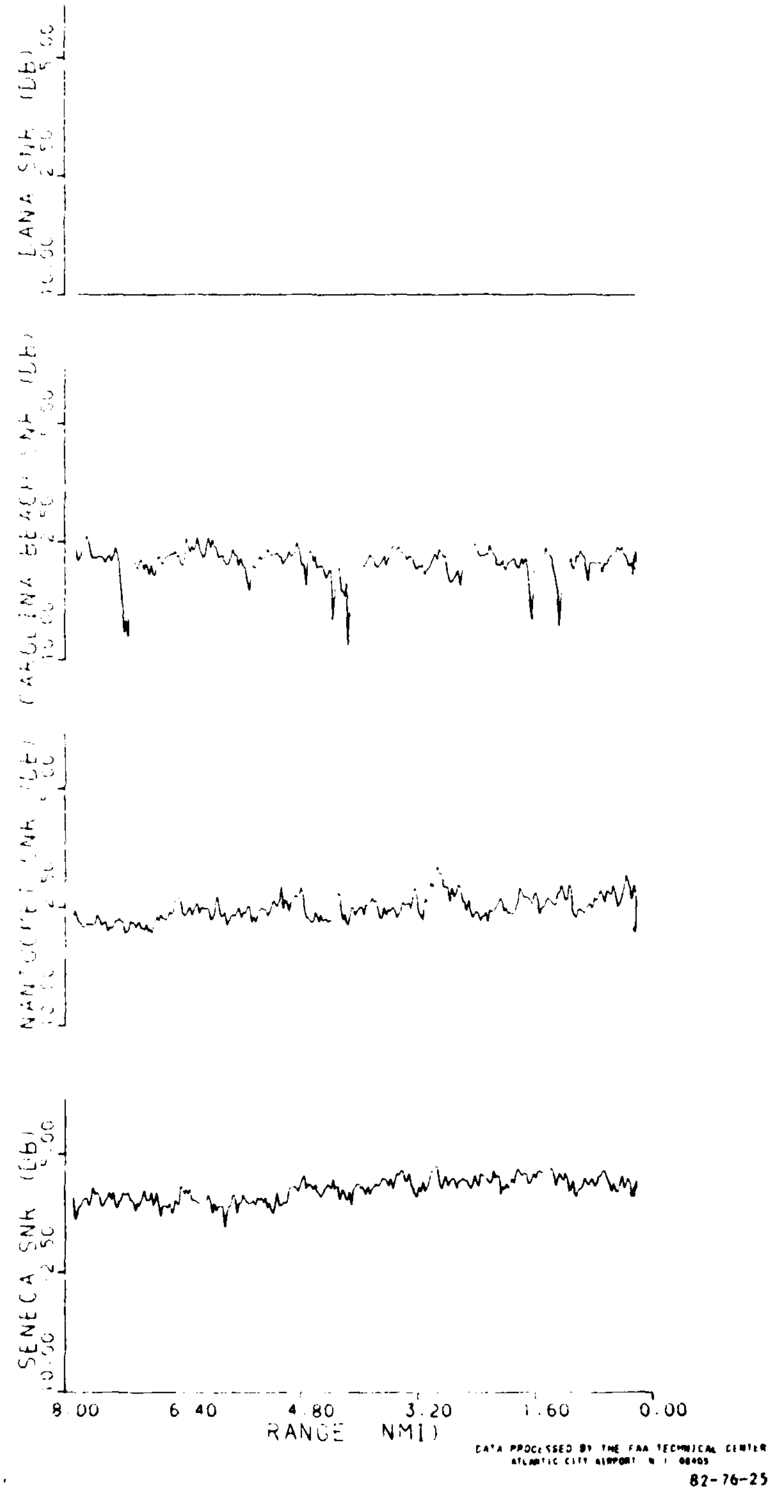


FIGURE 25. ATLANTIC CITY SNR

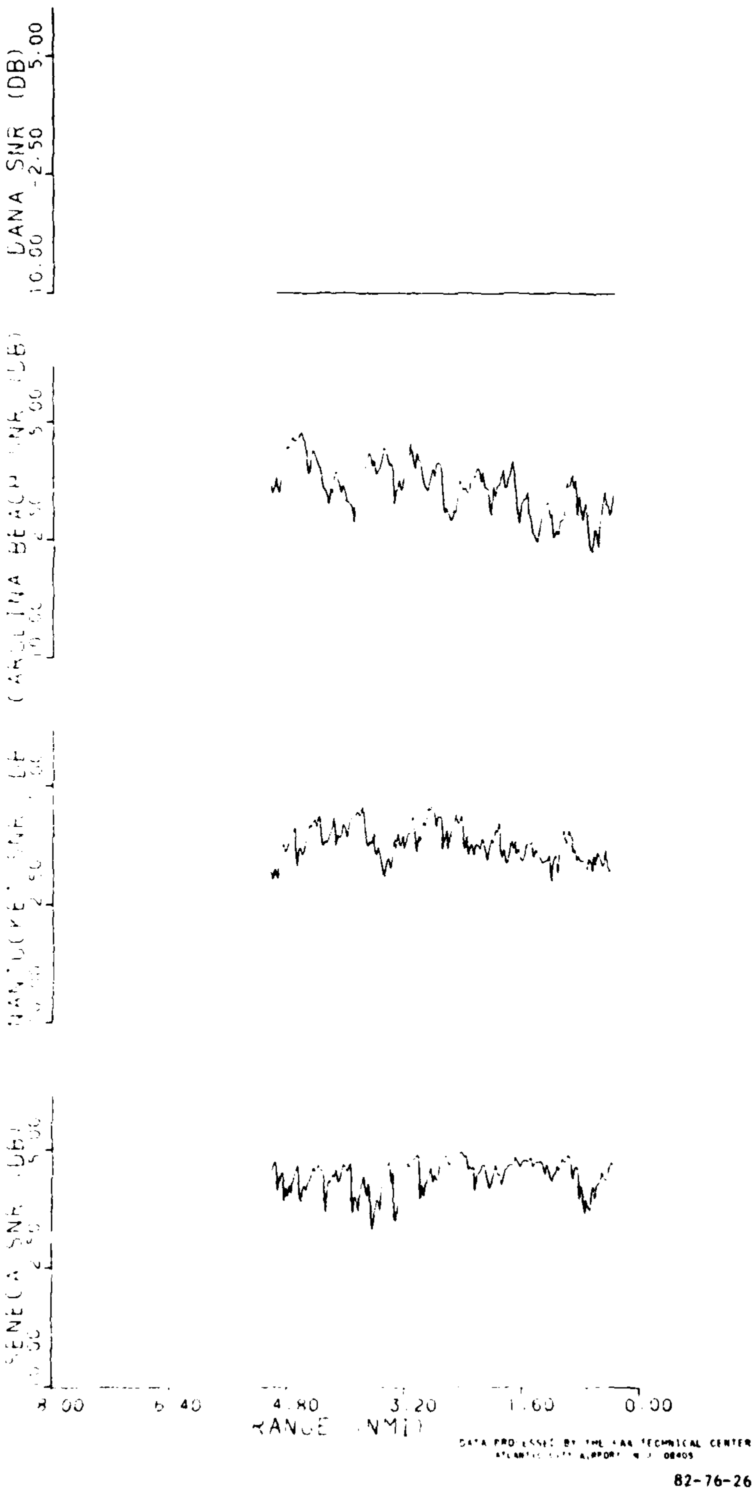


FIGURE 26. TRENTON SNR

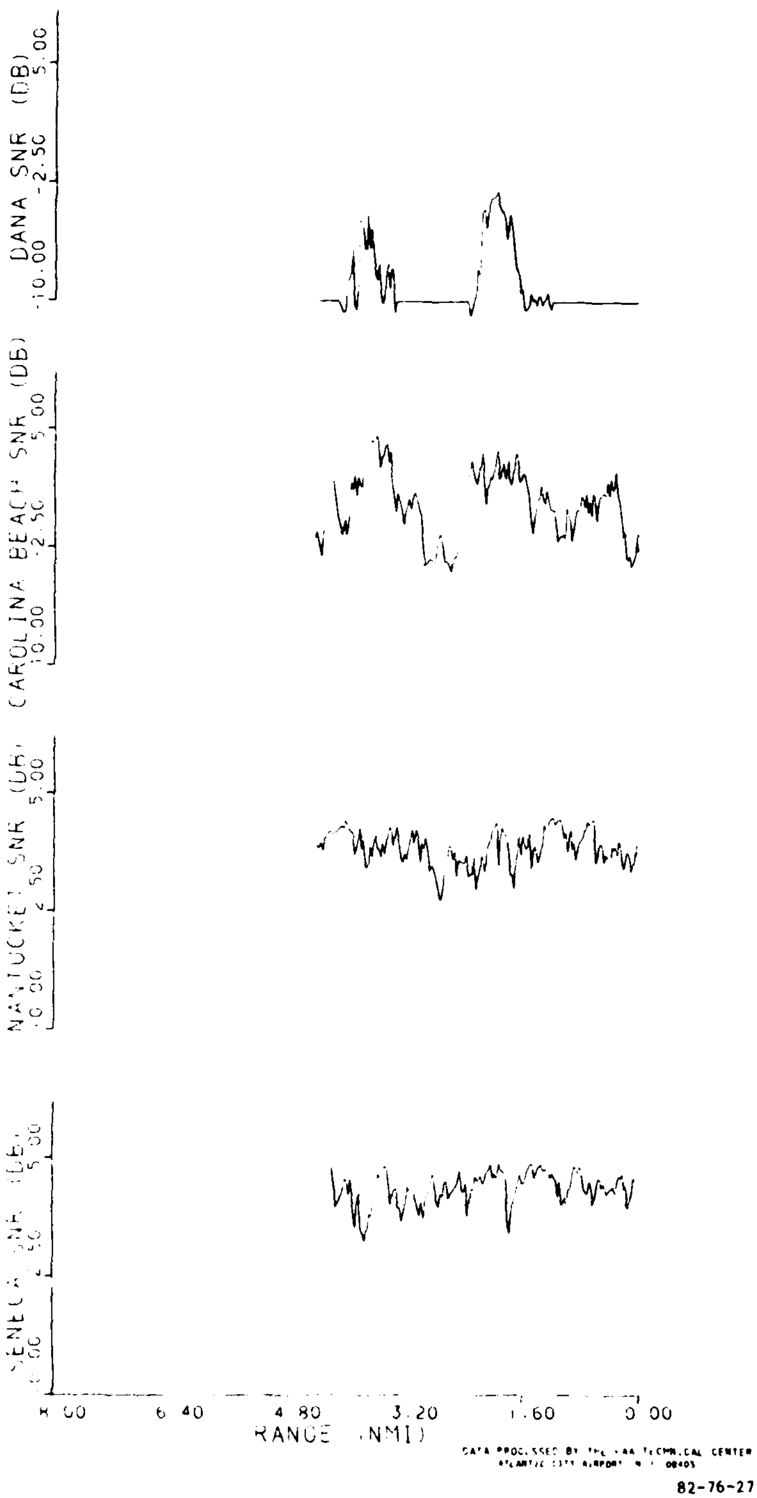


FIGURE 27. ALLENTOWN SNR

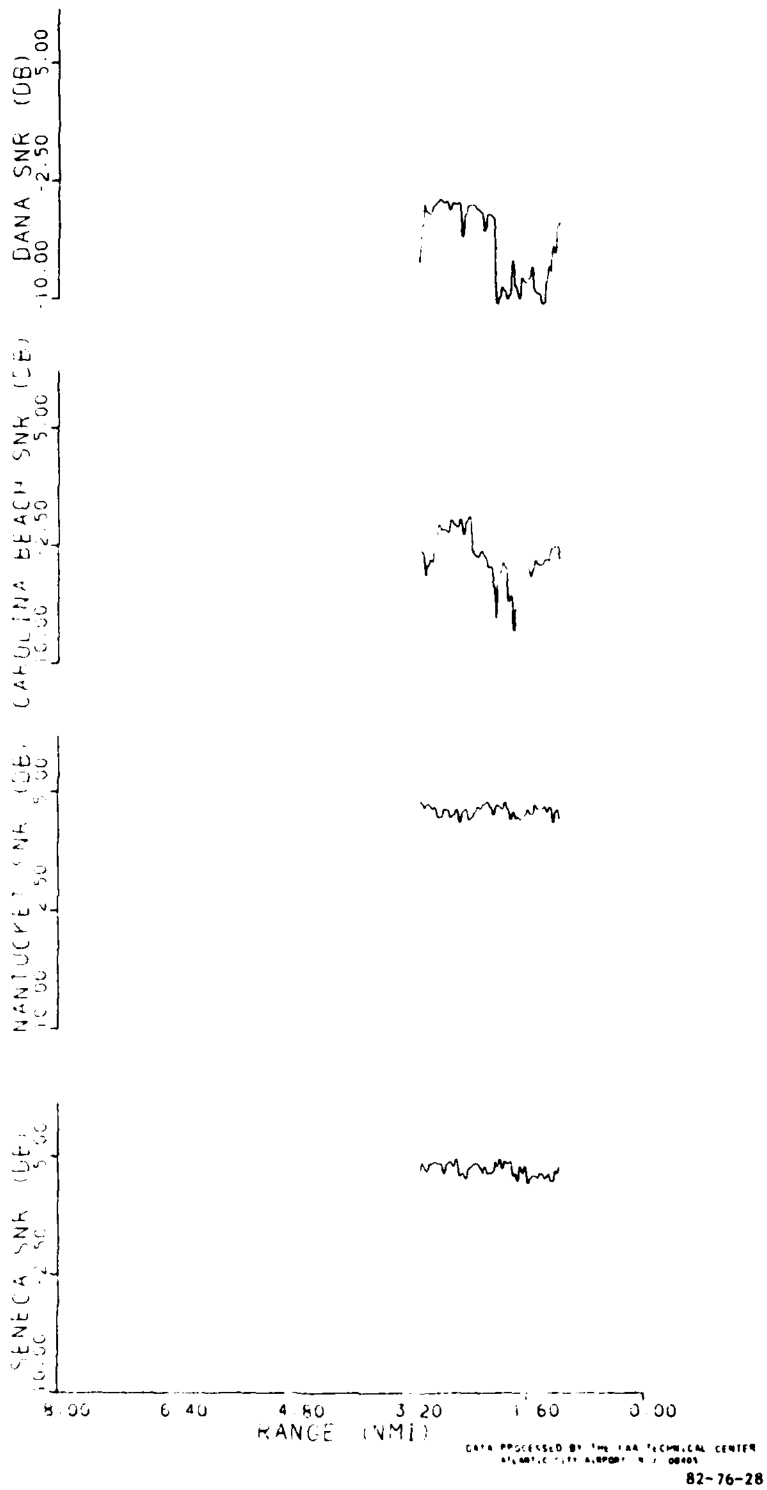


FIGURE 28. HARTFORD SNR

APPENDIX A

PORTABLE TRACKING SYSTEM

The portable tracking system consists of two major elements: the Portable Ranging System (PRS) and the postprocessing software (a Kalman filter) which reconstructs the approach trajectory. The operation of the PRS and the underlying theory of the postflight trajectory estimation software are discussed in the following sections.

PORTABLE RANGING SYSTEM

OPERATIONAL DESCRIPTION.

The Portable Ranging System is an off-the-shelf item manufactured by Motorola, Inc., known as the Mini Ranger III System. This system consists of a receiver-transmitter unit with antenna, a range console, and four reference stations with antennas. These units operate on the basic principle of pulsed radar ranging systems. The receiver-transmitter interrogates and waits for replies from each reference station, while the range console times the transmission delay. The range console converts the measured time delay to a range measurement, which is available in a parallel binary coded decimal (BCD) format for use by peripheral equipment. Range measurement accuracy is claimed to be approximately 3 meters in a static situation. Dynamic accuracy will be discussed in appendix B. The Mini Ranger included a four-code commutation option permitting the range console to interrogate four reference stations, in groups of two, on alternate measurement cycles. The original commutation board purchased from Motorola yielded a range measurement cycle time of 500 milliseconds. A four-code commutation board was designed and fabricated at the Federal Aviation Administration (FAA) Technical Center to reduce measurement cycle time to 200 milliseconds.

During the measurement cycle, the receiver-transmitter sends pulse coded interrogations to two reference stations. These transmissions are decoded by the interrogated reference station, which responds with a coded transmission. When five sequential interrogations produce five replies from a reference station, the averaged time count is stored in data interface latches as the range to the reference station. Range measurements are taken from a group of two reference stations (codes 1 and 2) for 200 milliseconds, and then from the second group of two reference stations (codes 3 and 4).

The four range measurements are recorded once every 200 milliseconds through the interface in the aircraft system's coupler, and stored on a floppy disk or tape recorder under control of the data collection software resident in the data collection computer. The program tests the contents of the real-time clock for an elapsed time of 200 milliseconds, thus determining start of a data collection period. On four consecutive data collection periods, four sets of the system's range data are collected and temporarily stored in a buffer memory. During the fifth 200 milisecond period, range data, current time from the airborne time code generator, and all other airborne data are collected and stored in a buffer memory. After the fifth data collection period is completed, data are permanently recorded and the data collection cycle is reinitiated. It is important to note that range measurement cycles and data collection cycles are asynchronous with each other. Ramifications of this will be clarified in the next section.

RANGE DATA PROCESSING

Printouts of the system's range measurements recorded during developmental flight tests indicated that certain types of problems (exhibited as range errors) occur which can be eliminated or reduced by postflight processing raw range measurements prior to updating the Kalman filter. Intermittent multipath, loss of signal, wild value range measurements, and time skew between the four range measurements are typical problems which fall into this category.

Time skew between the range updates is a result of the asynchronous operation between the four-code commutation board and the data collection interface. The asynchronous range measurement and data collection cycles cause the updated range measurements to occur randomly throughout the recorded data. Thus, it is necessary to search backward in time for the most recent range measurements and extrapolate each forward to the update time (airborne time during fifth collection period). Range data are searched and time occurrence is estimated based on a nominal 200-millisecond spacing of recorded values. Range selection is accomplished by comparing measured ranges to predicted ranges computed from extrapolated position coordinated from the Kalman filter, and substituting the predicted range if tolerances functionally dependent on ground speed are exceeded. Signal loss is indicated by two identical sequential range measurements and is corrected by inserting a predicted range. Finally, the range measurements are filtered by an alpha-beta tracking filter which extrapolates the ranges forward in time with a filtered range rate term. Beta is set to 0.7 to allow for adequate dynamic response. Initial values for the range tracking filter are set to zero.

Intermittent multipath effects are reduced by this technique. Continued multipath reception must be eliminated by choosing ground sites to provide unobstructed line-of-sight along the approach path.

OPTIMAL TRAJECTORY ESTIMATION

KALMAN FILTER.

All measurements necessary to reconstruct approaching helicopter trajectories were recorded by the Airborne Data Collection System. Eight measurements consisting of four ranges to known ground reference positions, barometric pressure altitude, barometric altitude rate, inertially derived track angle and ground speed, and Kalman filter theory provide an optimal linear filtering technique for estimating the state vectors (three-dimensional local cartesian position and velocity vectors) from noisy measurements.

A Kalman filter was developed (in-house at the Technical Center) in the form of postflight processing software, which provides a minimum error (linear mean square) estimate of position and velocity vectors.

Development of a specific filter required a dynamic system model of helicopter motion, a measurement model which related recorded data to states in the dynamic system model, a method of determining initial state vectors, and statistical knowledge of random processes associated with each model.

DYNAMIC SYSTEM MODEL.

Treating motion in three uncoupled coordinate axes simplifies the discrete dynamic system model. Final specification of the discrete dynamic system model requires a measure (variance) or random accelerations.

A discrete system model consisting of double integrators driven by zero mean uncorrelated random acceleration is assumed for each cartesian coordinate axis. Assumed square root values of acceleration variances are 9.8 m/sec/sec in X, Y axis and 12.1 m/sec/sec in the Z axes.

MEASUREMENT MODEL.

Choosing a right hand cartesian coordinate system with x and y axes aligned to north-east directions and origin located at some fixed arbitrary point on the earth's surface leads to a simplified measurement model. Surveyed geodetic coordinates of four reference stations are converted to local coordinates (flat earth approximations are employed) and entered into four simultaneous three-dimensional nonlinear range equations. Formulating derivatives of each range equation with respect to state vectors yields linearized, position-dependent weighting functions (direction cosines) for a model of range measurement.

Barometric pressure altitude is corrected for earth curvature and local pressure datum, and modeled as a direct measurement of coordinate Z. Barometric pressure altitude rate is modeled as a direct measurement of Z velocity. Inertial ground speed is resolved into X and Y velocities by trigonometric functions (sine, cosine) of inertial track angle. Each measurement is treated as containing unbiased, uncorrelated additive noise. An assumed total error budget is presented in table A-1.

INITIALIZATION.

Initial position vectors are estimated by solving four simultaneous range equations in three unknowns (X, Y, Z). The over-determined (more equations than unknowns) nonlinear set of equations are linearized and solved by Newton's iterative method, employing pseudoinverses of direction cosine matrices recomputed at each iteration step. Iteration begins with a guess of the initial position coordinates (X=0, Y=0, Z=barometric altitude), and terminates upon completion of five iterations, or sooner if a computed two-dimensional residual position error is less than 305 meters. Upon successful determination of an initial position vector, current measured values of X, Y, Z velocities become initial velocity vector estimates. Errors in initial state extimates are assumed to be unbiased and uncorrelated random variables. An assumed error budget of initialization errors is presented in table A-2.

SOFTWARE IMPLEMENTATION.

The previously described Kalman filter has been implemented in double precision FORTRAN and imbedded in the data reduction program which provides the position error data contained in this report. This implementation is a modified version of a Kalman filter previously designed and tested at the Technical Center. The newer version includes earth curvature correction and provides a flag which indicates an initialization settling period is in effect. During the 21-second settling time, the position should not be used for error analysis.

TABLE A-1. TOTAL MEASUREMENT ERROR BUDGET

Measurement	1σ
Range	5.0 m
Barometric Altitude	7.6 m
Barometric Altitude Rate	3.0 m/s
X, Y Velocity	2.0 m/s

TABLE A-2. INITIAL ESTIMATE ERROR BUDGET

Estimate	1σ
Position (X or Y)	305 m
Position (Z)	7.6 m
Velocity	3.0 m/s

APPENDIX B

PORTABLE TRACKING SYSTEM PERFORMANCE TESTS

A series of flight tests was conducted at the Federal Aviation Administration (FAA) Technical Center for the purpose of evaluating the accuracy performance of the portable tracking system. Early tests consisted of low approaches to runways 4 and 13 at the Atlantic City Airport, with four reference stations placed at surveyed points at opposite ends of each runway. The results indicated that the system could provide adequate accuracy with additional hardware/software modifications. These improvements were implemented and a second series of tests was designed to simulate conditions typical of remote base operations. These tests were conducted as full dress rehearsals of operational procedures, thus affording all personnel the opportunity to become familiar with assigned responsibilities.

Several weeks before the flight tests the ground reference station sites were surveyed with JMR-4 satellite survey sets. Ground sites were chosen to create baseline geometry similar to situations encountered at remote airfields. Line-of-sight is a very important consideration and will often dictate baseline geometry; a desire to stay within boundaries of small airfields restricts baseline lengths to a maximum of 2,500 meters in most cases. Two basic patterns were selected, a diamond-shaped array and a "T"-shaped array, with no baseline greater than 2,500 meters. A second series of approaches to runway 4 was flown with four reference stations placed at satellite surveyed sites, which formed a diamond-shaped configuration when viewed from the approach end of runway 4. The FAA Technical Center's modified Nike-Hercules radar tracked the helicopter and recorded its position at a 10 hertz (Hz) rate. Data were collected to perform a preliminary performance evaluation of the developed system.

Nike-Hercules tracking tapes were processed on the FAA Technical Center's Honeywell model 66/60 computer to transform azimuth, elevation, and range measurements at the radar site into the local X, Y, and Z coordinates. Processed radar data were time merged (+50 millisecond skew tolerance) on a PDP-11-34 Minicomputer (manufactured by the Digital Equipment Corporation (DEC)) and stored on magnetic tape. Data from merged data tapes were subsequently transferred onto magnetic disks for faster access by data analysis software.

Printouts of processed radar data, airborne data, and merged data were generated and visually examined to determine start and stop times, which were entered into a data analysis program. This program searched for the start time, initialized the Kalman filter algorithm, processed range data, generated filtered estimates of helicopter position, computed errors (differences) between filtered estimates and position reference (Nike-Hercules tracking data), and accumulated number of data points, sums of errors and sums of squared errors. When a stop time was encountered the data analysis program printed means, standard deviations (sigma) and root-mean-square (rms) values of the radial distance errors, and terminated operation. All analysis software was written in FORTRAN using double precision computations.

The numerical results (table B-1) of this analysis showed that the system was on the verge of meeting the specified criteria of 61.4 meters total radial distance error (95 percent confidence level). This criteria is based on one-tenth of the allowable area navigation (RNAV) system crosstrack error for nonprecision

approaches (AC 90-45A). In fact, an empirical count of errors inside and outside this bound show the system to be within 61.4 meters 98 percent of the time (2,062 out of 2,106).

These data were examined more closely, and it was determined that a settling time of 20 iterations of the Kalman filter was necessary to eliminate transient behavior due to initialization errors. Secondly, an earth curvature correction model was incorporated into the Kalman filter software. A third change was the adjustment by 6 meters of the position of one beacon for the second series of approaches to runway 4. The data were reprocessed with these changes to the analysis software with very satisfactory results. The numerical results presented in table B-2 show that the system meets the 61.4 meter criteria by all measurements considered. Finally, a count of the errors falling inside and outside the 61.4 meter circle shows 1,877 of 1,886 or 99.5 percent of errors fall inside the specified limit.

TABLE B-1. PORTABLE TRACKING SYSTEM RADIAL DISTANCE ERROR STATISTICS (METERS)

Runway 13 T Ground Site Geometry

Segment	Samples	Mean	2σ	2 rms	Mean +2
1	162	22.3	20.0	48.8	42.3
2	169	25.6	49.0[3]	70.7[4]	74.6[2]
3	216	26.8	27.9	60.3	54.7
4	166	27.0	24.1	59.2	51.1
5	93	22.3	14.2	46.8	36.5
Subtotal	806	25.1	30.6	60.0	55.7

Runway 4 Diamond Ground Site Geometry

Segment	Samples	Mean	2σ	2 rms	Mean +2
6	111	29.7[1]	18.2	62.1[2]	47.9
7	255	27.5	26.0	60.7	53.5
8	287	28.7	34.7	67.1[2]	63.4[2]
9	275	26.4	24.9	58.2	51.3
10	289	27.8	26.4	61.5[2]	54.2
11	83	23.2	228.6	54.3	51.8
Subtotal	1300	27.5	27.7	61.6[2]	55.2
Summary	2106	26.6	28.8	61.0	55.4
Worse Case		29.7[1]	49.0[3]	70.7[4]	78.7[5]

(1) Worse case mean
(2) Fails 61.4 meter criterion
(3) Worse case 2σ
(4) Worse case 2 rms
(5) Worse case mean + worse case 2σ

TABLE B-2. MODIFIED KALMAN PORTABLE TRACKING SYSTEM RADIAL DISTANCE ERROR STATISTICS (METERS)

Runway 13 T Ground Site Geometry

Segment	Samples	Mean	2σ	2 rms	Mean +2
1	142	22.1	13.6	46.3	35.7
2	149	21.4	11.0	44.3	33.4
3	196	26.8	28.4(2)	60.7(3)	55.2
4	146	27.9	23.4	60.5	51.3
5	73	22.3	15.4	47.2	37.7

Runway 4 Diamond Ground Site Geometry

Segment	Samples	Mean	2σ	2 rms	Mean +2
6	91	10.1	18.4	27.3	28.5
7	235	10.4	23.8	31.6	34.2
8	267	12.1	21.7	32.5	33.8
9	255	9.4	17.0	25.3	26.4
10	269	11.9	11.5	26.4	23.4
11	63	12.8	4.6	26.1	17.4
Worse Case		27.9(1)	28.4(2)	60.7(3)	56.3(4)

(1) Worse case
(2) Worse case 2σ
(3) Worse case 2 rms
(4) Worse case mean + worse case 2σ

APPENDIX C

PORTABLE TRACKING SYSTEM TEST RESULTS

The tracking system employed for this flight test employed a Motorola Mini Ranger III and a Kalman filter developed at the Federal Aviation Administration (FAA) Technical Center. An explanation of error trends involved in use of this tracking system is given here to facilitate analysis of graphical data presented in this report.

A prominent effect noticed in some of the crosstrack plots is an angular one in which crosstrack terms of each of the three navigation systems change as ranges to the Mini Ranger beacons decrease. Several sources of this error exist, which may act singly or in combination under the different conditions imposed at different subject airports.

The bandwidth of the Kalman filter affects its settling time and could cause the angular effect. In some beacon configurations and conditions the solution may not settle completely until the aircraft has traveled several miles along the approach path. While the optimal filter solution may not be obtained until several hundred data samples are processed, the induced tracking system error is not great enough to require discarding the data. Resultant position accuracy is still within the prescribed error boundary.

Another effect arises from the geometry of the beacon positions and relative aircraft position. At long distances the relatively short distance between beacons provides less lateral discrimination of position than when the aircraft moves closer. This results in relatively poorer determination of crosstrack distances at longer ranges, while along-track determination remains basically unaffected.

In addition to the second effect, errors in determination of relative beacon coordinates may combine to produce an angular shift in aircraft position determination. This will, however, also influence the along-track position error. Of the three effects, this can potentially cause the greatest position errors. Surveys of beacon positions with accuracies better than 15 feet were made to minimize the effect of this source on position determination accuracy.

Another characteristic of the tracking system may appear as a ramping effect, predominantly in the crosstrack direction. This may possibly be caused by an alpha-beta filter extrapolation used in the Kalman filter program which provides beacon range inputs for the Kalman filter. The alpha-beta tracker provides range estimates to each beacon at 200-millisecond intervals from the measured, raw asynchronous ranges measured during flight. The combination of the asynchronous update and the alpha-beta implementation may cause the ramping effect noted in some of the data.

Another characteristic of the tracking system results in fairly large excursions in position determination error during extended beacon dropouts not requiring Kalman filter reinitialization. During these dropouts, the alpha-beta tracker provides range estimates for the unavailable beacon. Since the tracker is essentially nonlinear, it should not be used during beacon dropouts of more than approximately 10 seconds duration. It provides degraded accuracy during periods where position

determination would otherwise be outside accepted limits. Excessive use of the tracker-determined range to replace an inactive beacon range will result in unacceptable degradation of performance. The Kalman filter must then be reinitialized, with a resultant loss of 20 to 30 seconds of data encountered while initialization is completed.

Resultant error from all sources has been measured at the FAA Technical Center using an X-band precision tracking Nike-Hercules instrumentation radar as a reference. Accuracy was determined to be within 61.4 meters, within a 95 percent confidence interval.

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